

# Chapter 4

## Energy Conversion and Transformation Plants

### 4.1 Overview

The energy necessary for end-use has different forms (mechanic, luminous, electric, thermal); it can be of different origin, and there are different processes that make it available.

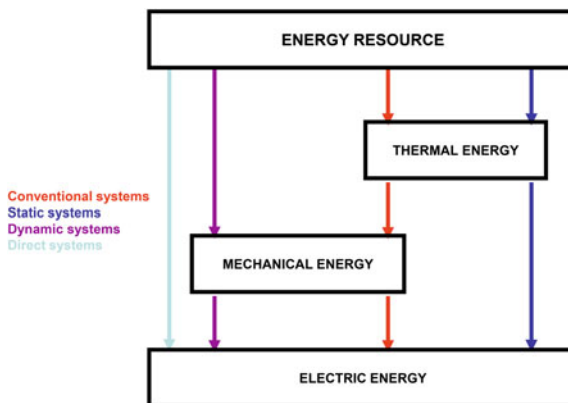
The primary sources directly available in nature are not always conveniently and efficiently usable in the processes from which the most suitable form of energy for end-use can be obtained. For this reason, in almost all cases, primary sources undergo *conversion* or *transformation processes*, whose outcome is indicated by the so-called *secondary sources*.

*Conversion* processes are characterised by a *passage from one energy form to another* (for instance from electric power to mechanic power, as it happens in electric motors), whereas in *transformation* processes the *form of energy remains the same although with different characteristics* (as it happens, for instance, in electric transformers, which vary in terms of current intensity and voltage, keeping—net of the losses—the same power; or in heat exchangers in which only energy flow characteristics, like temperature, vary, but not the form of energy).

### 4.2 Energy Conversion Plants

As already mentioned, energy production processes include the set of single energy transformation and conversion processes that allow to transform/convert the resource used in the desired energy form. According to the technology adopted, these processes can be higher or smaller in number and of different types. For the production of electric power, for instance, conversion plants can be classified according to the number and type of conversion and/or transformation processes used (Fig. 4.1).

**Fig. 4.1** Electric power production processes



In the so-called *conventional systems* (thermo-electric power plants) the chemical energy of fuels is converted into heat through a combustion process; such heat is converted into mechanical energy, through a thermodynamic<sup>1</sup> cycle, which is in turn converted into electric power by an electric generator.

In the so-called *dynamic systems* the resource used is available in the form of mechanical energy (i.e. water kinetic energy in hydroelectric power plants and wind kinetic energy in wind power plants), *transformed* to obtain mechanical power on a shaft, which can in turn be converted into electric power by a generator.

In *static systems* (owing their name to the fact that they have no moving components), as magneto-hydrodynamic, thermoelectric and thermionic, the chemical energy of the fuel is converted into heat<sup>2</sup> that is directly transformed (without the intermediate passage in the form of mechanical energy) into electric power through the electromagnetic, thermoelectric and thermionic conversion processes.

Finally, *direct systems* directly convert the resource exploited into electric power: these types of systems are the *photovoltaic plants*, which directly convert solar radiations into electric power through a photoelectric process, and the fuel cells, that convert the chemical energy of a fuel (generally hydrogen) directly into electric power through an electrochemical process.

All the systems mentioned above can also envisage other transformation processes such as *mechanical variation systems* (either reduction or increasing), for instance introduced in order to obtain a suitable number of revolutions of the rotor of the generator starting from the number of revolutions of the turbine shaft, and *systems for the transformation of the voltage and frequency* of the electric power produced in order to obtain the suitable utilisation characteristics.

This paragraph contains the description of the most common conversion plants used for the production of the main energy vectors: heat, electricity and hydrogen.

<sup>1</sup> This introduces a thermodynamic limit to the conversion process efficiency, the so called *Carnot efficiency*.

<sup>2</sup> These plants can also be powered with solar, nuclear, or other types of energy.

Table 4.1 summarizes the systems under consideration with the relevant conversion.

### 4.2.1 Mechanical Energy-to-Electric Power Conversion Plants

#### 4.2.1.1 Hydroelectric Plants

##### *Plant Cycle and Layout*

The cycle for the production of electric power through hydropower plants can be summarized as follows: due to the effect of the solar energy, the water of seas, rivers and wet surfaces evaporates. The masses of damp air, transported by winds, encounter favourable condensation conditions and originate rainfalls. The water that falls on mountains has a potential mechanic energy that generally disperses through friction by flowing downstream; by limiting this waste by means of suitable pipes, such energy, instead of being dissipated in the form of heat, is transformed (unless unavoidable losses occur) into usable kinetic energy; through a hydraulic turbine, then, the kinetic energy of water is transformed into mechanic work.

Basically there are two plant layouts: *run-of-river plants*, that use the flow rate of the river by following its natural variation, and *reservoir plants*, which allow to fill reservoirs with volumes of water hence making them available according to energy needs, clearly within the volume limits of the reservoir itself. The works that are necessary for the construction of a hydroelectric power plant include:

- *Weirs*: normally, in reservoir plants, intake works consist of dams, whereas in run-of-river works there are simple weirs. Dams are taller since, besides intercepting the water flow, also create a reservoir that is useful to regulate flow rates. Weirs, on the contrary, are works of moderate height that generally limit the level of water upstream within the line of the riverbed.
- *Intake works*: which allow to transport water from the weir to the plant. They are made up of an intake work (endowed with grids and interception devices) followed by a diverting channel that can be either free-surface or a pressure pipeline. Free-surface channels generally have a trapezoidal section and can be dug into the ground and endowed with a concrete coating; pressure pipelines, on the contrary, have a round section and are made with steel pipes.
- *Adduction and transportation work at the plant*: these pipes begin from the forebay reservoir or from the surge tank and bring water to the machines of the plant; they are heavily inclined and made of round steel plate. They always have head and foot valves that allow to prevent the passage of water when needed.
- *Disconnection work*: at the end of the diversion channel is located a *forebay reservoir* if the diversion is an open channel, or a *surge tank* in case of a pressure derivation. The disconnection aims at reducing the effects of the sharp changes in the flow rate caused by the regulation of the power to be produced,

**Table 4.1** Some energy conversion plants

Conversion		Plant	Conversion and transformation
From	To		
Mechanical	Electric	Hydroelectric power plants	Transformation of the potential energy of water into kinetic energy Transformation of kinetic energy into mechanical power on a shaft Conversion from mechanic energy into electric power
		Wind power plants	Transformation of the kinetic energy of the air into mechanic power on a shaft Conversion from mechanic energy into electric power
Radiant	Electric	Photovoltaic plants	Direct conversion
Chemical	Electric	Thermoelectric plants (gas, steam and combined gas-steam plants)	Conversion of the chemical energy of a fuel into thermal energy (combustion) Conversion of thermal energy into mechanic energy (thermodynamic cycle) Conversion of mechanic energy into electric energy
		Fuel cells	Direct conversion
Chemical	Mechanic	Internal combustion engines	Conversion of the chemical energy of a fuel into thermal energy (combustion) Conversion of thermal energy into mechanic energy (thermodynamic cycle)
Chemical	Electric	MHD (Magneto Hydro Dynamics)	Conversion of the chemical energy of the fuel into thermal energy of a plasma conversion of thermal and mechanical energies og the plasma into electric one
Radiant	Thermal	Flat-plate collectors	Direct conversion
		Concentrators	Direct conversion
Thermal	Chemical	Chemical reactors <sup>a</sup>	Direct conversion
Electric	Chemical	Electrolysers	Direct conversion
Radiant	Chemical	Photoelectrolysis	Conversion of radiant energy into electric energy Conversion of electric energy into chemical energy
Electric	Thermal	Compression heat pumps	Conversion of electric energy into mechanic energy (refrigerant fluid compression) Conversion of mechanic energy into thermal energy (heat flow)
		Peltier effect heat pumps	Direct conversion
Electric	Radiant	Incandescent lamps	Conversion of electric energy into thermal energy (Joule effect) Conversion of thermal energy into luminous radiant energy
		Discharge lamps	Direct conversion

<sup>a</sup> “Direct conversion” is referred to the only water thermolysis chemical plant that uses heat for the scission reaction. According to the heat production procedures, the plant as a whole operates a transformation of chemical energy (in case heat is produced from the combustion of fossils) or a conversion from radiant energy to chemical energy in case heat is produced in concentration solar plants.

**Table 4.2** Criteria for the construction of hydroelectric power plant

Function of the work	Reservoir plant	Run-of-river plant
Weir	Dam	Weir
Intake	Pressure	Free-surface
Transportation	Pressure tunnel	Open-air or tunnel
Disconnection	Surge tank	Forebay reservoir
Adduction at the plant	Pressure pipeline	Pressure pipeline
Energy production	Open-air or cavern	Outdoor
Drain	Outdoor or tunnel	Outdoor

introducing at the end of the diversion channel a tank that can either temporarily absorb the overflow or provide additional overflow in case of need. These works also aim at reducing the effects of pressure variations (*water hammers*) in water channels because of the manoeuvres on the machines of the plant.

- *Plants*: they can be open-air with the building above the ground, sunken or in a vertical shaft, underground or as caverns. They include the turbine, the electric transformer and all the auxiliary components.
- *Outlet works*: they are made up of an open channel or a pressure channel that gives back the water flow used in the watercourse, hence bringing water from the plant to the watercourse.

The criterion at the basis of the construction of these works varies according to the type of plant made as shown in Table 4.2.

### *A Brief Mention on Hydraulic Machines*

The type of turbine to be installed in a hydroelectric plant depends on the head available and on the flow rate. Figure 4.2 shows the diagram relating to the use of the three most widespread turbines: *Pelton*, *Francis* and the *bulb-type turbine* or *Kaplan*. Following the principle of similitude, the two parameters, head and flow rate, define the *characteristic velocity* or the *specific speed*, a parameter that characterises “hydraulically similar” machines. This parameter can be expressed with the following formula<sup>3</sup>:

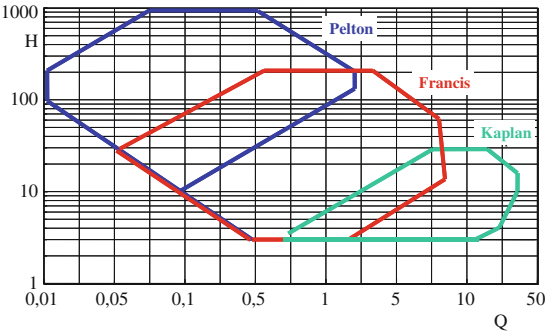
$$N_s = \frac{n\sqrt{N}}{H_m^{5/4}} \quad (4.1)$$

where  $N_s$  is the *characteristic velocity*,  $n$  the *nominal speed of the machine*,  $N$  the *nominal power* and  $H_m$  the *hydraulic head*.

<sup>3</sup> It can also be expressed according to mass flow rate  $Q$ , instead of power  $N$ , that is to say:

$$N_{sq} = \frac{n\sqrt{Q}}{H_m^{3/4}}$$

**Fig. 4.2** Graph showing the utilisation of Pelton, Francis and Kaplan turbines according to the flow rate and the hydraulic head



**Table 4.3** Characteristic number for the different types of turbines

Turbine	$N_{sq}$
Pelton	5–22
Francis	20–100
Kaplan	100–300

The characteristic velocity has an important practical meaning since, given the same hydraulic head and power, it is proportional to the rotation speed of the machine, and since the weight of the machine (and thence its cost) decreases as speed increases, machines are developed with the highest possible characteristic velocity. Table 4.3 shows the indicative values of the characteristic velocity of the most commonly used hydraulic turbines<sup>4</sup> [1].

### The Net Head

The *net head* of a hydraulic turbine is the *difference of hydraulic loads*, i.e. of the *mechanic energy owned by the liquid, between two conventional sections immediately upstream and downstream the machine*. These sections are chosen with operational criteria for the different types of turbines.

Indicating with  $H_i$  and  $H_o$  the hydraulic loads, with  $z_i$  and  $z_o$  (in m) the heights (as compared to an arbitrary reference), with  $p_i$  and  $p_o$  (in  $\text{kg/m}^2$ ) pressures, and with  $V_i$  and  $V_o$  (in m/s) the speeds corresponding to the input and output sections of the machine mentioned above, the net head expressed in meters is:

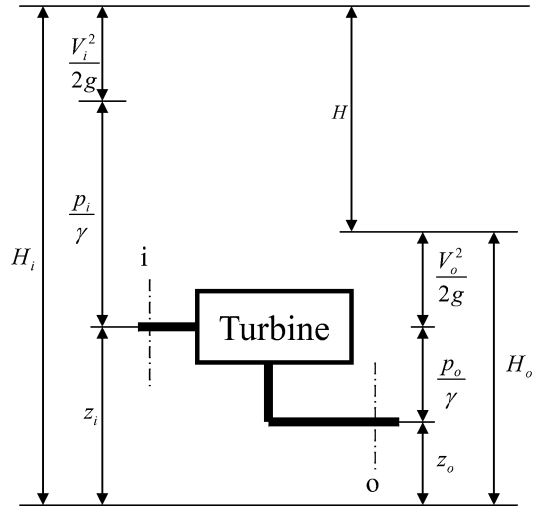
$$H = H_i - H_o = \left( z_i + \frac{p_i}{\gamma} + \frac{V_i^2}{2g} \right) - \left( z_o + \frac{p_o}{\gamma} + \frac{V_o^2}{2g} \right) \quad (4.2)$$

where  $\gamma$  is the specific gravity of water (in  $\text{kg/m}^3$ ).

The reference chart is shown in Fig. 4.3:  $z$  is the geometrical height,  $p/\gamma$  is the static head and  $V^2/2g$  is the velocity head.

<sup>4</sup> The values shown are obtained by expressing  $n$  in revolutions/min.,  $Q$  in  $\text{m}^3$  and  $H_m$  in m.

**Fig. 4.3** Layout of a hydroelectric plant



In case of impulse turbines<sup>5</sup> (Pelton) the impeller completely rotates free in the air, hit by one or several jets, therefore the outlet pressure is the atmospheric pressure, namely  $p_o = p_a$ . Furthermore, the outlet velocity is to be considered as null, considering calculations in the corresponding energy (kinetic) dissipated in the turbine (the turbine is charged with a loss that as a matter of fact is not related to it). Therefore in case of impulse turbines, the following applies:

$$H_o = z_o + \frac{p_a}{\gamma} \quad (4.3)$$

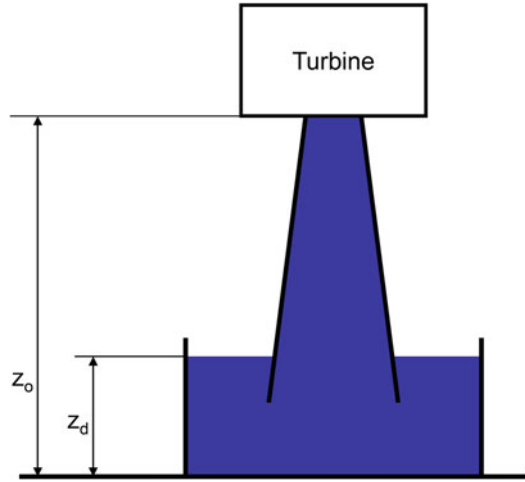
As an outlet section, the height of the touching point of the jet axis at the average diameter of the wheel is considered; in case of horizontal axis two-jet turbines, the average of the heights of the touching points defined above is considered. In case of multi-jet turbines, the height of the plane containing them is taken into consideration. As an inlet section, the connection flange between the pressure pipeline and the machine is considered. By replacing (4.3) in (4.2), it follows that the net head for impulse turbines is:

$$H = \frac{V_i^2}{2g} + \frac{p_i}{\gamma} + z_i - z_o - \frac{p_a}{\gamma} \quad (4.4)$$

In reaction turbines (Francis and Kaplan), the outlet pressure is different from atmospheric pressure due to the presence of the diffusion-aspiring pipe. This allows not to lose the net head corresponding to the height of the outlet section of the machine at the discharge canal. As concerns Fig. 4.4 by applying the

<sup>5</sup> In general, action (or impulse) turbines are those in which there is no pressure difference in the operating period between inlet and outlet from the impeller, whereas in reaction turbine the outlet pressure is lower than the one at the inlet of the impeller.

**Fig. 4.4** Layout of a hydraulic turbines diffuser



Bernoulli's principle (with no losses) between the outlet section of the machine (*o*) and the discharge section (*d*), it follows that:

$$\frac{V_o^2}{2g} + \frac{p_o}{\gamma} + z_o = \frac{V_d^2}{2g} + \frac{p_d}{\gamma} + z_d \quad (4.5)$$

At the discharge, velocity can be considered as null and pressure is the atmospheric one, therefore (4.5) it becomes:

$$\frac{V_o^2}{2g} + \frac{p_o}{\gamma} + z_o = \frac{p_a}{\gamma} + z_d \quad (4.6)$$

From which, bearing in mind (4.2), it is possible to write the equation of the net head for reaction turbines:

$$H = \frac{V_i^2}{2g} + \frac{p_i}{\gamma} + z_i - z_d - \frac{p_a}{\gamma} \quad (4.7)$$

To determine the expression of the hydraulic head according to the height of the intake reservoir, of the discharge canal and of the machine, as regards Fig. 4.5 by applying the Bernoulli equation between the intake section (*in*) and the inlet section to the machine (*i*), it is possible to obtain:

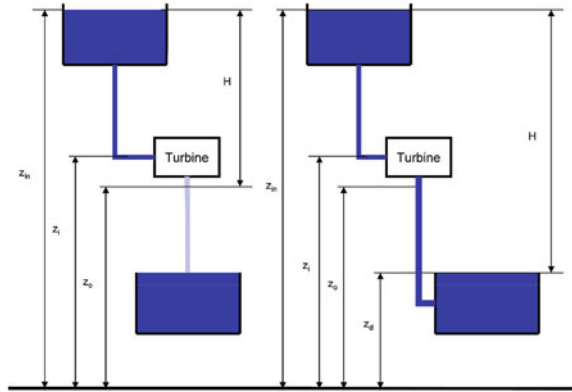
$$\frac{V_{in}^2}{2g} + \frac{p_{in}}{\gamma} + z_{in} = \frac{V_i^2}{2g} + \frac{p_i}{\gamma} + z_i \quad (4.8)$$

In the intake section, velocity can be considered as null and pressure is the atmospheric one, therefore (4.8) becomes:

$$\frac{p_a}{\gamma} + z_{in} = \frac{V_i^2}{2g} + \frac{p_i}{\gamma} + z_i \quad (4.9)$$



**Fig. 4.5** Layout of a hydroelectric plant with impulse and reaction turbine



**Fig. 4.6** Pelton turbines



By replacing (4.9) in (4.4) and in (4.7) the expressions of the net head for impulse turbines ( $H_{imp}$ ) and reaction turbines ( $H_{react}$ ) are obtained:

$$H = z_{in} - z_o \quad (4.10)$$

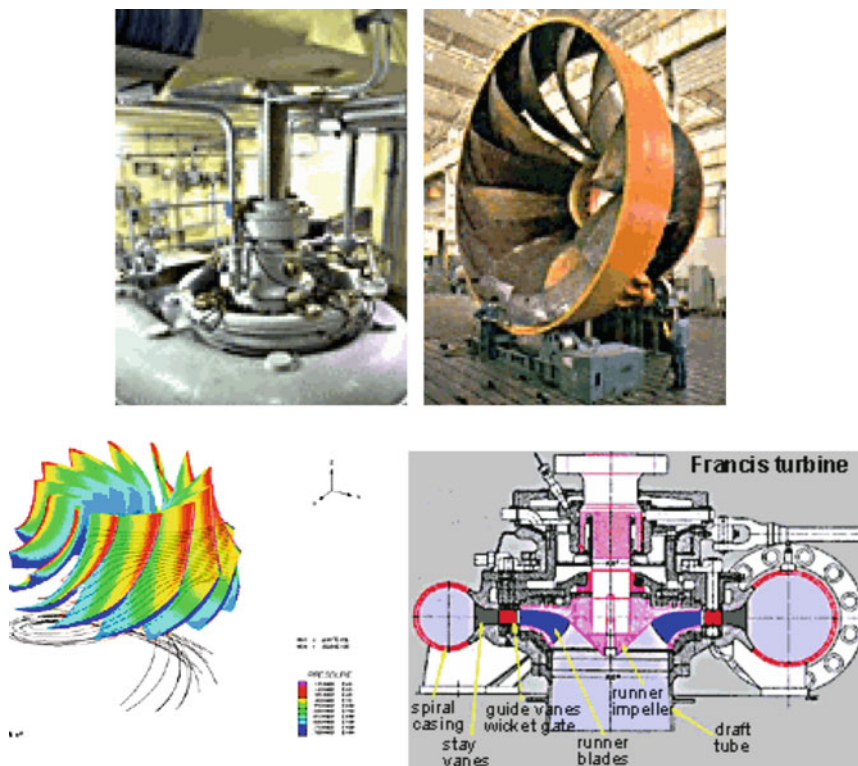
$$H = z_{in} - z_d \quad (4.11)$$

It is therefore possible to see how in impulse turbines the net head corresponding to the height of the outlet section from the machine is lost compared to the discharge canal.

### *Field of Application and Efficiency of Hydraulic Turbines*

It is now possible to state that the Pelton turbines are suitable for the highest net heads (impulse turbines, Fig. 4.6), the Francis reaction turbines are used for intermediate heads (Fig. 4.7), whereas for small heads the Kaplan reaction turbines are used (Fig. 4.8). The fields of application, in general, are those shown in Table 4.4 [1].

In case of not-too-high heads, it is economically convenient to use the Francis reaction turbines, even when it would be possible to use the Pelton ones. With the



**Fig. 4.7** Francis turbines

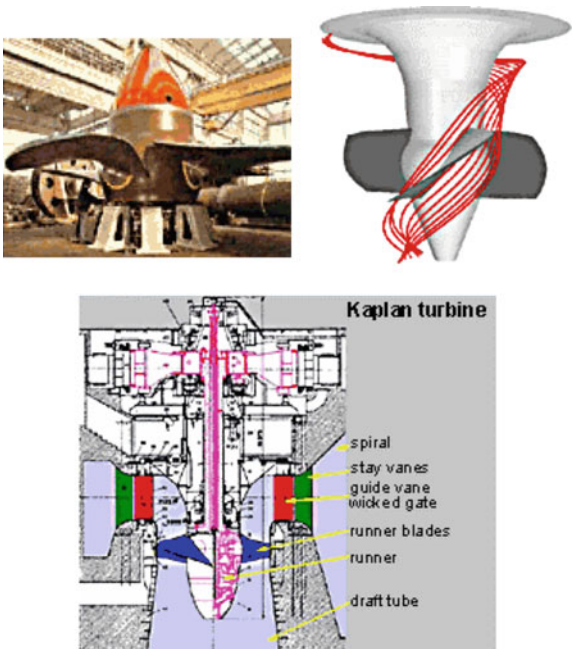
continuous fine-tuning of the fluid-dynamic design of blades and with the experience acquired in the solution of problems related to high heads, as well as the use of high discharge heads, there is a continuous trend by Francis turbines to trespass the Pelton turbines' field of application. As the head increases, however, the economic convenience of the Francis turbines decreases, due to the worsening of seal and cavitation problems.

In case of small heads with large flow rates, Kaplan turbines are used: with them, the adjustable blades allow not only to keep a good efficiency in terms of adjustment, but also a good operation in case of variations of the net head—including considerable ones.<sup>6</sup> For this reason, despite of the construction complexity and, therefore, of high costs, the Kaplan turbines tend to trespass the Francis turbines' field of application.

As concerns efficiency, Pelton and Kaplan turbines are endowed with an adjustment system (variation of the jet section with Pelton, variation of the propeller-blade angle with Kaplan) that allows to keep a good efficiency for wide flow

<sup>6</sup> For small heads (i.e. 10 m), head variations, although limited in absolute terms, entail variations that from a percentage viewpoint are relevant for the head itself.

**Fig. 4.8** Kaplan turbines



**Table 4.4** Fields of application of hydraulic turbines

Turbine	Hm (m)
Pelton	>500
Francis	70–500
Kaplan	<70

rate variations (given the same hydraulic head and power); the Francis turbine has no adjustment systems and its efficiency markedly decreases for flow rate variations—including limited ones.

*Pumped-storage Plants*

One particular feature of hydraulic plants is that demand of they allow the construction of *pumping plants*, which, in the situations of low electricity, use electric power to pump upstream the water.

These devices are typical of pondage installations in which a pump (Francis turbines are reversible, they can work both as a turbine and as a pump, and therefore in some cases there is one machine only) takes water from the basin downstream back to the basin upstream, consuming electric power (usually in the night lower demand). The alternator, being a reversible engine, while pumping works as an electric motor. It is obvious, while considering efficiency, that the electric power consumed in the pumping phase is higher than the one produced during generation, and therefore the entire process wastes part of the electric

power globally produced. However, some considerations are needed. The pumping process allows not to drastically intervene, interrupting the water flow and therefore the production of electricity in some cases. This interruption would entail management problems as well as energy waste higher than the energy spending entailed by the pumping plant. And, what is more important, this process makes the conversion requested to thermoelectric plants more efficient, since their performance are very much influenced by sudden variations of loads than in the case of hydroelectric plants.

In case of not too high hydraulic heads (up to 600 m) it is possible to use the Francis turbine that, since it is a reversible machine, during the pumping process, in rotating inversely, can also act as a pump. This solution, which only includes a hydraulic machine, is more convenient from the economic viewpoint.

If the head is higher, it is necessary to use two different hydraulic machines: one Pelton turbine and one pump. The Pelton turbine, working as an impulse turbine, is always above the level of the afterbay reservoir, whereas the pump, in order to avoid cavitation problems, must be placed below the level of the lower basin; in this way the two machines are located distant from one another, and this entails construction problems linked to the length of the shaft connecting the two machines. This solution is more expensive than the previous one.

An alternative solution that allows to eliminate the problem of the length of the shaft (excessive lengths may entail problems linked to shaft vibrations, at the point of making the work practicably impossible), consists in the creation of two separate plants in overlapping caves, one at a higher height with Pelton-alternator groups, the other one at a lower height with pump-electric motor groups. The cost of these plants heavily exceeds the one of single-cave plants.

Another solution, successfully tested and implemented consists in making a multistage pump working as a turbine by making it turn in the opposite direction. The adoption of particular profiles of the impeller allows to obtain a good efficiency both in terms of generation and pumping. This type of machines allows to adopt binary groups (i.e. groups with one hydraulic machine only) for high heads (600–1,300 m) and high power (larger than 150 MW) [2].

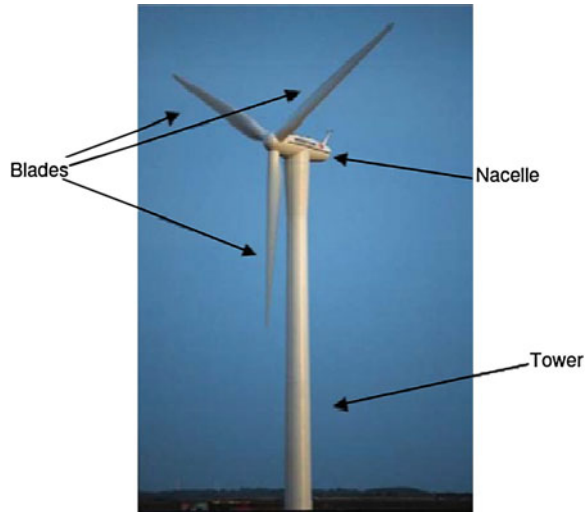
One limitation for multistage reversible groups is the impossibility of adjusting the power supplied since the hydraulic machine has no diffuser and works “all or nothing”.

### *General Classification of Hydroelectric Plants*

The power of hydraulic plants varies from some tens to thousands of kW. Obviously there are different construction criteria for the different sizes; the following categories of plants can be identified:

- Micro-hydraulic up to 100 kW.
- Mini-hydraulic from 100 kW to 1 MW.
- Small-hydraulic from 1 to 3 MW.
- Hydraulic over 3 MW.

**Fig. 4.9** Main components of a wind turbine



Larger hydroelectric power plants (small-hydraulic and, most of all, hydraulic) need a long construction time and remarkable initial investments, especially due to the civil engineering works that are necessary. The construction costs for this type of plant is very high, whereas the cost for the production of the electric power supplied is among the lowest ones in the different types of plants.

The potential energy-electric power conversion efficiency amounts to nearly 80% and is mainly determined by the efficiency of turbines (about 90%), by energy waste in pipelines (1–2%) and by the efficiency of the alternator (around 90%).

The utilisation depends on the type of plant: in run-of-river plants, the variation of the power supplied follows the natural course of the flow rate available and the number of hours of operation per year is, on average, 5,000. In basin plants, on the contrary, it is possible to adjust the power supplied according to the demand and reach the highest number of hours of operation per year (nearly 5,800).

#### 4.2.1.2 Wind Power Plants

##### Overview

Wind power plants convert the kinetic energy of moving air masses into mechanic energy of blade rotation. The set of blades represents *the rotor* of the wind turbine, the *nacelle* contains all the other elements that are necessary for energy conversion, and the tower acts as a support (Fig. 4.9).

In general, the mechanic energy linked to blade rotation can be exploited in two different ways:

- As mechanic energy, for instance to operate a pump (windpumps).
- Transforming it into electric power (aero-generators, also commonly called wind turbines).

Having considered the remarkable and growing importance that the latter machines have taken in world market, further on in this chapter reference is exclusively made to wind power plants destined to the production of electric power.

Apart from this first distinction, wind turbines are subject to several classifications, that are shown below.

### *Classification of Wind Turbines*

A first classification divides wind machines on the basis of the position of the rotation axis of blades; it is possible to find *horizontal axis turbines* and *vertical axis turbines*. Vertical axis turbines, as the Darrieus turbine, have had little fortune until today, despite of some evident advantages as the possibility of working at very low wind regimes and the automatic alignment with the instantaneous direction of the wind. Their main limit is represented by a lower conversion efficiency compared to horizontal axis turbines.

As concerns the position of the rotor and of the nacelle, wind turbines can be placed *upwind* or *downwind*.

The almost universally adopted solution is *upwind*, in which moving air “encounters” the rotor and subsequently the nacelle and the tower. This position allows to minimise the disturbance of the tower and the nacelle against the wind before it encounters the blades.

The *downwind* configuration is exclusively used in particular cases, for some small-sized yaw turbines, since the nacelle passively aligns to the direction of the wind. This choice, however, shows the huge disadvantage of the interference of the tower and the nacelle with the air flow, entailing the following consequences:

- Increase of the oscillating forces acting on the machine;
- Lower conversion efficiency;
- Increase of acoustic emissions.

Wind turbines can be employed to feed isolated individual users, or to simultaneously supply electric power to the electricity grid. When a wind turbine has to be connected simultaneously to the electric network (which is the most frequent case nowadays), it is necessary that the energy produced has strict quality features in terms of voltage and frequency. Assuming to generate electric power through an alternator connected to the rotor of the turbine, it must be considered that the rotation speed of the alternator depends on the frequency through:

$$n = \frac{60 \cdot f}{p} \quad (4.12)$$

where  $n$  is the rotation speed of the alternator (revolutions per minute),  $f$  is the mains frequency<sup>7</sup> (Hz) and  $p$  is the number of polar couples of the generator.

The number of polar couples is limited, due to their size and to the cost of the generator, to a maximum of 3. Therefore, in case of a frequency of 50 Hz it is possible to obtain the rotation velocity of 3,000 rpm (1 polar couple), but also 1,500 rpm (2 polar couples) and 1,000 rpm (3 polar couples). If we consider, for instance, a rotation speed of 1,000 rpm and a turbine with a diameter of 40 m, the peripheral speed of the tip of the blade amounts to over 2,000 m/s. It is evident that such a speed would entail an overstress for the blades. It is therefore necessary to differentiate the rotation speed of blades from the speed of the generator.

Many manufacturers solve this problem by inserting a reduction gear with a ratio of about 1:50. This is a configuration with a direct connection to the mains and entails a constant rotation speed for the rotor of the wind turbine. The consequence of this option is a non-suitable behaviour whenever conditions differ from those of the design.

An alternative option is to use *axial flux permanent magnet slow generators*. A generator with 30 poles, for instance, rotates with a speed of 200 rpm. This rotation frequency entails a peripheral speed that is still acceptable for small-sized turbines (some tens of kW), due to the small standard radius. For instance, a turbine of 10–20 kW, with a diameter of 8 m, would have a speed at the blade tip of nearly 84 m/s corresponding to a rotation frequency of 200 rpm. Thanks to this configuration, it is possible to make a direct coupling between rotor and generator, avoiding the presence of the reduction gear, hence with a huge saving in terms of weight, cost and energy losses.

The most frequently adopted configuration to avoid the use of the reduction gear, however, is the one of the indirect connection to the grid. In such a configuration, a synchronous generator (alternator), directly connected to the rotor, produces electric power in multifrequency alternating current (since the rotation speed varies); this current is transformed into direct current by a *rectifier*, and subsequently transformed again into constant-frequency alternating current through an *inverter*.

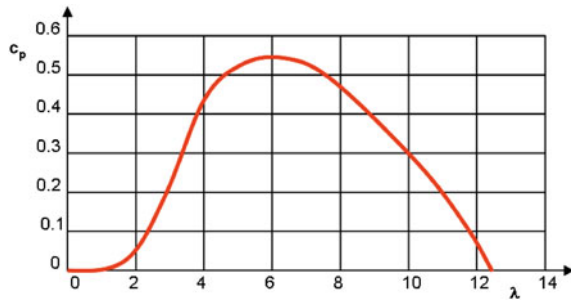
The disadvantages of this configuration are linked to the additional cost of transformation devices. The advantages include the possibility of avoiding the presence of the reduction gear and to obtain a variable rotation speed for blades, with the subsequent optimisation of efficiency for a wide range of wind speed.

The *tip speed ratio*,  $\lambda$ , is defined as the ratio between the maximum peripheral speed of the blade (that is to say the speed at the tip of the blade,  $v_p$ ), and wind speed ( $v$ ):

$$\lambda = \frac{v_p}{v} = \frac{\omega \cdot r}{v} \quad (4.13)$$

<sup>7</sup> 50 or 60 Hz (see Sect. 3.5.4.1).

**Fig. 4.10** Power coefficient as  $\lambda$  varies



Furthermore, the *power coefficient*,  $c_p$  is defined as the ratio between the energy transferred to the rotor and the one contained in the wind current. Please note that  $c_p$  is proportional to the efficiency of the machine, although it takes on higher values since it considers neither the mechanical loss in the other components (for instance the reduction gear), nor the electric ones in the generator.

The power coefficient of a wind turbine varies with  $\lambda$ , reaching a peak whenever a given value applies. Figure 4.10 shows the qualitative trend of the power coefficient according to  $\lambda$ .

*Fixed rotation speed turbines*, for which  $\lambda$  necessarily varies as wind speed changes, operate at optimal  $\lambda$  only for a particular value of wind speed. *Variable speed turbines*, on the contrary, operate at optimal  $\lambda$  in a wider field of wind speed values, since they are able to adapt their rotation frequency to the instantaneous velocity of the wind, therefore keeping the value of  $\lambda$  constant. The result is that the variable rotation speed allows an increase of average efficiency. The choice of the optimal number of blades for a wind turbine is linked to the  $\lambda$  ratio. The turbines with a high number of blades have a low value of the optimal ratio of peripheral speed ( $\lambda = 1$ ) and are therefore characterised by a low number of revolutions, given the same wind velocity. They show, however, a remarkable starting torque, and this is the reason why they are used for water pumping or for other purposes in which mechanic energy is directly necessary. The high torque demands a great strength for the rotor and therefore a high number of blades.

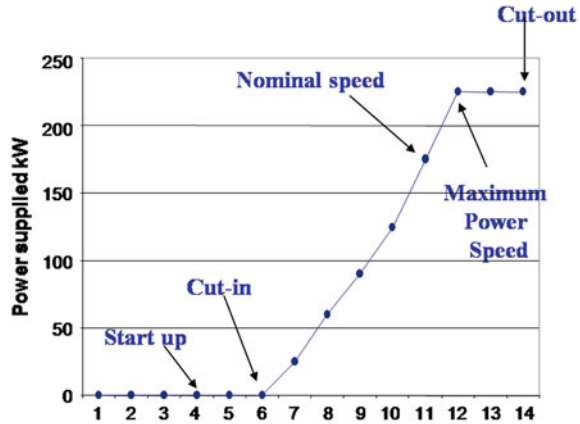
Conversely, the turbines with a lower number of blades are used for electric power generation and are characterised by a high rotation speed and a high value of  $\lambda$  ( $5 \div 8$ ).

Nowadays, turbines with  $\lambda > 8$  are not manufactured, since the level of noise, approximately proportional to the peripheral speed of the blade, would reach unacceptable levels.

The large-size turbines that are presently used for electric power generation are almost exclusively manufactured with three blades. The need for blades with a large diameter, in fact, entails high peripheral speeds at the tip of blades, given the same wind velocity. This means, in practice, a high value of  $\lambda$ . Three-blade turbines are then preferred, since they operate at the highest efficiency with high values of  $\lambda$ . The recent trend to manufacture turbines with two or even one blade is linked to the cost reduction that could be obtained. All the large-size turbines



**Fig. 4.11** Power supplied according to wind speed



belonging to the first generation were endowed with two-blade rotors. Nowadays a different approach is followed, according to which a three-blade rotor is preferred, given its more uniform weight distribution in the area swept out. This circumstance entails a higher uniformity of the stress on the structure and also a lower visual impact during the rotation of blades.

According to the present regulations for the certification of wind turbines, the resistance of components must be tested with less frequent and strong winds (between 50 and 70 m/s). It is readily evident that it is not convenient to design a machine able to operate at such values of wind speed, since the additional cost would be huge, while the increase of additional energy production negligible, having considered the low frequency of very strong winds. For this reason, designers prefer to adopt measures that reduce the power absorbed by a wind turbine as the wind speed increases, and put it “out of use” in case such velocity becomes excessive. According to international regulations, this operation includes two braking systems, one for operation and one for emergency. Namely, a *power regulation* is carried out. This operation consists of dispersing excess energy, besides a given value of wind velocity, in order to prevent damages to the plant.

Usually, there are *four running speeds* relating to wind turbines:

- Standstill rotor
- Partial load operation
- Adjustable nominal power operation
- Stop.

In order to characterise the operation of wind turbines, a series of values for the speed of the wind hitting the rotor are defined (Fig. 4.11).

Until the wind reaches a *minimum speed*, called “*cut-in*”, the energy transferred to the blades is not sufficient to overcome the inertia of the rotor and of the generator, and the turbine cannot then be started up. Subsequently, the *nominal speed* is defined, as the one at which corresponds the rated power of the machine. Between the “cut-in” and the nominal speed, the machine operates at a *partial*

*load*. In case of values higher than the nominal one, the turbine works in a *power control speed*, until reaching the “cut-out” speed, at which the machine is not exposed to the wind action any longer, in order to avoid structural damages. In any case, the resistance of the machine up to the *survival speed* is guaranteed. The indicative values of the speeds described for a modern turbine are summed up below:

- “Cut-in” speed: 3.5 m/s
- Nominal speed: 13 m/s
- “Cut-out” speed: 25 m/s
- Survival speed: 70 m/s.

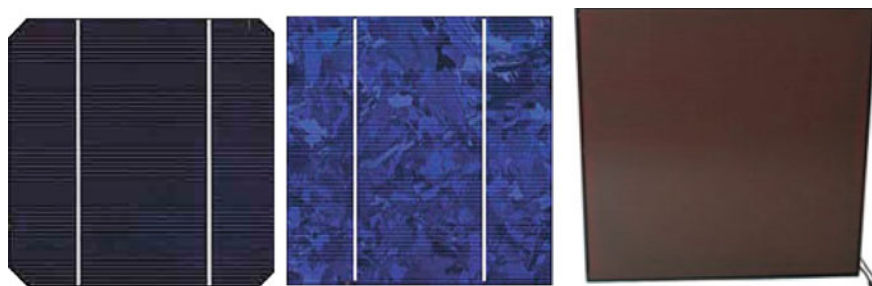
The most widespread methods for power regulation are the following:

- Pitch control allows to vary the pitch of blades by rotating them around their longitudinal axis, so as to “take them out” of the wind. Thanks to this control, in case of speed values exceeding the nominal one, the power remains constantly as the rated power. The pitch variation allows a mild control of power, although demanding a blade rotation mechanism as well as an active control of output power that controls the implementation of the pitch.
- *Stall* is based on the homonymous phenomenon. Stall consists in the detachment of the fluid vein from the surface of the blade as the wind speed increases. Following this detachment, the lift force decreases due to the rotation of blades, and the excess energy is dispersed in the form of vortexes. Compared to the control for pitch variation, the “passive” use of the stall phenomenon requires neither a mechanism of blade rotation around their longitudinal axis, nor a control mechanism. The stall, on the other hand, needs a high-level aerodynamic design and also leads to the development of vibrations on the wind machine.
- *Yaw*: the rotor is “taken out” by the wind through a rotation around the vertical axis.
- *Tilt variation*: the rotor is “taken out” by the wind through a rotation around the horizontal axis.

Normally, high-power turbines are controlled by stall or pitch variation, whereas small-sized ones by yaw or by tilt variation.

As a matter of fact, the yaw mechanism is used in all turbines to point the nacelle towards the direction of the prevailing wind, as this direction varies in time. This variation can be carried out passively, by means of a weathercock, or through an active control operated by an anemometer. The signal of the anemometer records the wind direction and transmits this information to the yaw system. The use of weathervanes is allowed for rotors with a diameter up to 10 m, because in case of larger turbines it would be too large to be economically convenient.

The power produced by wind turbines, as already underlined, depends on wind speed. The *nominal power* is the one that corresponds to the nominal speed for a given machine. The energy actually produced by a machine in a given period of time, normally 1 year, cannot be simply calculated by multiplying the nominal power by the number of operations hours, since speed varies in time.



**Fig. 4.12** Photovoltaic cells in single-crystalline, polycrystalline and amorphous crystalline silicon

The producibility of a wind turbine is therefore strongly related to the *speed distribution of the site* and can be expressed in *equivalent hours*, meaning the hours of operation at the nominal power that usually reach a maximum number of 3,000 per year. From an economic viewpoint, the use of wind turbines to generate electric power becomes convenient in those sites in which the equivalent hours of operation per year range at least between 1,500 and 2,000.

## 4.2.2 Radiant Energy-to-Electric Power Conversion Plants

These plants are based on the “direct” conversion of solar radiant energy into electricity as a consequence of the *photovoltaic effect*.

### 4.2.2.1 Photovoltaic Plants

#### The Photovoltaic Cell

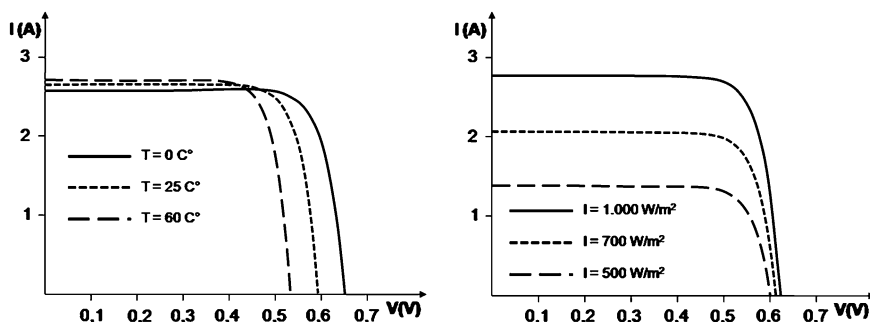
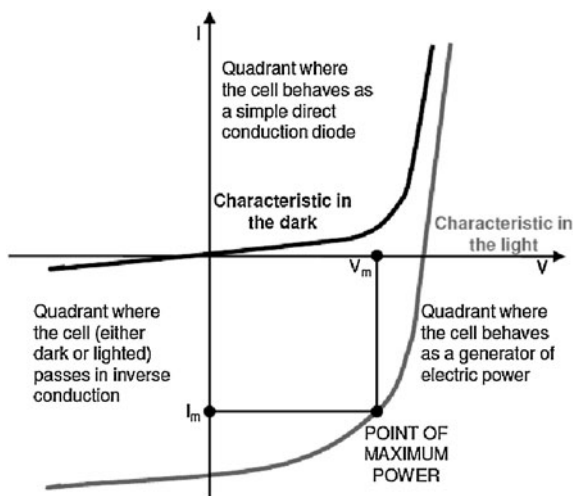
The element at the basis of photovoltaic devices is the *photovoltaic cell* (Fig. 4.12). It is available in different sizes and can be made of different materials. The most widespread cells are in crystalline silicon (monocrystalline and polycrystalline) and in amorphous crystalline.<sup>9</sup> A typical form is squared, with a surface of nearly 100 cm<sup>2</sup>, although larger cells can be manufactured.

The curve describing the trend of the current of the cell according to its voltage, called *characteristic curve*, shows the behaviour of the cell both in the dark and in the light (Fig. 4.13).

By applying a potential difference in the dark, there is a flow of current only if the value exceeds a given threshold.

<sup>9</sup> Other materials (for instance organic materials) are being studied.

**Fig. 4.13** Typical curve  $I$ – $V$  of a photovoltaic cell



**Fig. 4.14** Variation of curve  $I$ – $V$  with the temperature of the cell and with the solar radiation intensity

On the contrary, by exposing the cell to the light electric power is generated in any case; if the junction is in short circuit ( $V = 0$ ) a maximum current is generated ( $I_{sc}$ ), whereas in case of open-circuit ( $I = 0$ ), a maximum voltage is determined on the two sides ( $V_{oc}$ ). In the case of standard silicon cells ( $10 \times 10$  cm),  $I_{sc}$  is nearly 3 A, whereas  $V_{oc}$  amounts to about 0.6 V. Having considered that the power of a generator is the product of its voltage by the current generated, in the two cases described above the power will be null, and from the characteristic curve it is possible to identify the point in which the system provides the maximum power.

The characteristic curve of a cell depends, besides its *intrinsic properties* (the material), also on two important parameters: the *intensity of luminous radiation* and the *temperature of the cell itself* (Fig. 4.14). It is evident, therefore, that at the maximum power it takes different values as  $I$  and  $V$  vary; the corresponding values of current and voltage are called *current* ( $I_{pmax}$ ) and *maximum power voltage* ( $V_{pmax}$ ).

Temperature increase cause a decay in the electric performance of the photovoltaic device. In a silicon cell, for instance, whilst the short circuit current undergoes a negligible variation, the voltage of the open circuit decreases as temperature increases (nearly 2 mV/°C). The heating of a photovoltaic cell entails, therefore, an overall decrease of its performance.

Since photovoltaic system are powered by a variable source and since, as just analysed, their performance are linked to the characteristics of solar radiation. In order to quantify the performance of a photovoltaic cell (and more generally of whatever photovoltaic device), it is necessary to refer to precise conditions, known as *standard conditions*:

- *Radiation intensity* 1.000 W/m<sup>2</sup>
- *Cell temperature* 25°C
- *Solar spectrum* AM1, 1.5 (correspong to a solar zenith angle 4819).

The rated data of the power generated by a photovoltaic cell is expressed in *Watt peak* (Wp); the *peak power* is the one generated in the standard conditions mentioned above. The *conversion*, efficiency is the ratio between the electric power  $P$ , provided by the cell and the radiation power that strikes the frontal surface, expressed as a product of the density of incident radiation  $I$  (W/m<sup>2</sup>) and the area of the surface exposed  $A$  (m<sup>2</sup>):

$$\eta = \frac{P}{I \cdot A} \quad (4.14)$$

The *nominal conversion* efficiency is calculated in standard conditions: therefore the density of incident radiation  $I$  is 1,000 W/m<sup>2</sup> and by indicating with  $P_n$  the peak power of the cell:

$$\eta_n = \frac{P_n}{1,000 \cdot A} \quad (4.15)$$

The nominal efficiency of monocrystalline silicon commercial cells also reaches 18%; those in polycrystalline silicon do not exceed 14%, whereas those in amorphous silicon reach nearly 8%.

The power generated in operation is almost always different from the maximum nominal power. Two important factors influence, in fact, the output of a photovoltaic generator: *radiation intensity* and *temperature* of the photovoltaic cell (Fig. 4.14).

The first factor influences the short circuit current and subsequently the current generated at maximum power. One can approximately say that the short circuit current proportionally decreases as radiation decreases.

The second factor, on the contrary, acts on the open-circuit voltage and therefore also on maximum power. In this case as well it is possible to assume that the maximum power voltage undergoes a linear decrease with temperature increase.

The result is that the operating power decreases if compared to the reference value (maximum power or peak power).

### *The Applications of Photovoltaic Technology*

There are many possible applications of photovoltaic technology and range from the power devices of very few hundreds of Watt (mostly pocket calculators and watches) up to plants of several MWp.

In the past, having considered the prohibitive costs that characterised these systems, mainly *small-size applications* were developed since they did not require burdensome investments. However, as the cost of modules decreased, larger and larger applications gained ground until reaching the 90s with *photovoltaic plants*. They showed that high quantities of electric energy can be easily produced with photovoltaic technologies, and that the only limitation to their development is cost. If prices decrease to levels that allow to compete with electricity production from traditional sources, there will be no more barriers to its spreading. The constant decrease of the cost of modules led the sector's operators to perform a careful evaluation of those costs that are not directly depending on the photovoltaic module. Thanks to this new approach, the attention of scholars and designers shifted from large size power plants (high costs for bearing structures) to smaller integrated systems in buildings, which represent the most promising solution for photovoltaic systems.

### *The Photovoltaic Plant*

Starting from *finished cells* it is possible to constitute *modules*, by adapting the voltage and the current of the group of cells to users' needs. The voltage of a single cell, in fact, is on average low for all materials (around 0.5 V), whereas, by connecting cells in series, the desired potential difference is obtained, which is the sum of the various potentials. Several panels, electrically connected in series, constitute a *string* whose voltage will be the sum of the voltage of the different panels forming the string itself, whereas the current will be the same as in a single panel. Several strings, electrically connected in parallel, make up the *photovoltaic field*: the voltage of the field is the same as one of the strings, and the current is the sum of the current of the stack.

Another component of photovoltaic plant is the *maximum power point tracker* (MPPT). The MPPT allows working current and voltage to be the maximum power ones at any operating (incident solar radiation, temperature) and load condition.

The other components of plants vary according to the following types of plants:

- *Stand-alone systems*
- *Grid-connected systems*.

Stand-alone systems envisage a *storage system* that guarantees current supply even in the hours of lower lighting or of dark. The elements making up a stand-alone system include the *photovoltaic field*, the *charge controller*, the *battery* and, in case the equipment must be powered through alternating current, an *inverter*.<sup>10</sup>

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<sup>10</sup> Device converting the inlet direct current into alternating one.

The storage system is normally *electrochemical* (*electric accumulators*); the choice is between lead–acid batteries, the most widespread ones, nickel–cadmium and nickel–metal hydride batteries, lithium batteries which are more expensive.

The charge controller acts as a protection of accumulators. In fact, according to the type of batteries selected, some precautions must be made on the voltage at which the charge and discharge phases are carried out. In case the threshold voltage is exceeded, the charge controller interrupts the current, and it allows current to flow again only when voltage decreases below the threshold value.

This type of plant is used in those cases in which the electric grid is absent or hardly accessible (i.e. remote houses, mountain refuges, pumping systems, telecommunications systems, repeater stations, mark buoy, etc.).

The systems connected to the grid release the excess of energy generated in the hours of sunshine and take it in the hours in which the generator is not sufficient to meet the overall demand. They necessarily include an inverter that transforms the direct current produced by a photovoltaic generator into an alternating current as similar as possible to the one supplied by the grid. However, the type of periodical function that represents the current trend over time have a perfectly sinusoidal trend, differently from the inverters in stand-alone applications, which almost always can provide a square wave signal (low-quality of the signal) without creating any problems to the equipment they supply. In this case it is necessary to obtain an output signal with a high degree of purity. It is also necessary that the current injected in the grid is “in-phase” with the grid itself. Quite often, grid-connect system—for either simplicity, or feed-in tariff advantages—supply all the produced electricity to the grid even when integrated in buildings.

### *Energy Produced by a Photovoltaic System*

Since the nominal power (peak power) of a photovoltaic plant is only a reference value, it is fundamental to evaluate the actual quantity of energy that the plant itself is able to actually produce in a given period of time.

Besides the nominal characteristics of the plant itself (number and efficiency of panels), such quantity of energy depends also on other parameters such as:

- *The insolation conditions* in the installation site: the incident solar energy (kWh/m<sup>2</sup> year);
- *The position of modules in space*: tilt, azimuth and eventual shadings;
- *Balance of system (BOS) efficiency*: the efficiency of all the other systems of the plant (inverters or accumulators), the losses in connection cables, etc..

Once the site characteristics (latitude, altitude and horizontal radiation) and the position of panels (tilt, azimuth and eventual shadings) are known, it is possible to calculate the incident specific energy  $H_p$  (kWh/m<sup>2</sup>), on panels (Fig. 2.9): once the useful surface of panels  $A$  (m<sup>2</sup>) is known, the total incident solar energy on panels is calculated. The electric power (in direct current)  $E_{dc}$  (kWh) produced by the photovoltaic field is:

$$E_{dc} = H_p \cdot A \cdot \eta_p \quad (4.16)$$

Such energy shall be converted into alternating current and then transferred to users, and in these operations part of the energy is lost. The BOS efficiency measures the amount of said losses<sup>11</sup>. The *useful energy*  $E_u$  produced by the plant is, therefore:

$$E_u = E_{dc} \cdot \text{BOS} = H_p \cdot A \cdot \eta_p \cdot \text{BOS} \quad (4.17)$$

By referring to the surface unit and assuming  $\eta_p = 16\%$  and  $\text{BOS} = 90\%$ , (4.17) becomes:

$$E_u = E_{cc} \cdot \text{BOS} = H_p \cdot 0.144 \quad (4.18)$$

that is to say the useful energy accounts for 14.4% of the incident solar radiation. In considering, as an example,  $H_p = 1.800 \text{ kWh/m}^2 \text{ year}$ <sup>12</sup> it follows that with  $1 \text{ m}^2$  of panels it is possible to produce nearly 260 kWh/year.

Equation 4.17 can be written according to the nominal power of the plant  $P_n$  (kW). By definition of the nominal efficiency of the panel<sup>13</sup>:

$$\eta_p = \frac{P_n}{A} \quad (4.19)$$

By replacing (4.19) in (4.17) it follows that:

$$E_u = H_p \cdot P_n \cdot \text{BOS} \quad (4.20)$$

As regards the nominal power unit, the useful energy is a fraction (equal to BOS) of the specific incident solar energy. The product of  $H_p$  by BOS represents the equivalent hours for the photovoltaic panel. On the basis of the hypotheses a 1 kWp plant produces nearly 1.600 kWh/year.

### *Costs and Sizing General Criteria*

The sizing of a photovoltaic system can follow different approaches, according to whether a stand-alone or a grid-connected plant is taken into consideration.

A stand-alone system, in fact, must in any case guarantee to users the meeting of the consumptions envisaged. The entire set of the photovoltaic system and of

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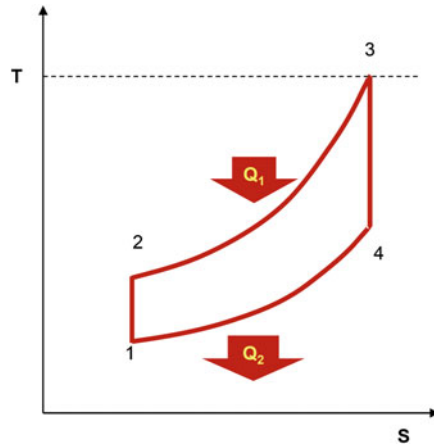
<sup>11</sup> As a matter of fact, the definition of BOS efficiency often includes other factors of loss that are not linked to other parts of the system, but still to the module and in particular to some of its peculiar operating conditions. These are the *losses due to the effect of temperature*, *losses due to reflection on the frames of modules*, etc. In the case of isolated systems, the battery charge and discharge process entails an additional loss, which can be estimated as amounting to nearly 10% of energy.

<sup>12</sup> Solar radiation in Rome with a tilt of  $30^\circ$ , azimuth equal to 0 and without shading.

<sup>13</sup> Standard conditions provide for an incident radiation of  $1 \text{ kW/m}^2$ .



**Fig. 4.15** The ideal Joule cycle



storage batteries must therefore be able to meet the entire electric power needs, and sizing is consequently strictly related to consumption.

In case of grid-connected systems, on the contrary, there is not any new constraint, since users can be directly supplied through the electric grid, which acts as an almost unlimited storage capacity. The starting points for sizing can therefore be different from consumption and, in particular, they can be linked to the surface available or to the initial investment budget, as well to feed-in tariff rules.

The cost of photovoltaic modules is obviously different according to the size of the plant to be developed, and is continuously evolving. Photovoltaic modules are presently sold “on a power basis”, meaning that, for instance, several polycrystalline modules are sold at the same price as a minor quantity of single-crystalline modules provided that the nominal power of the two groups is the same.

Prices are continuously evolving, also in consideration of the incentives in force, and the present trend indicates a progressive reduction of prices.

### 4.2.3 Chemical Energy-to-Electric Power Conversion Plants

#### 4.2.3.1 Gas Turbine Plants

##### Thermodynamic Cycle

The basic reference cycle is the Joule cycle (Fig. 4.15<sup>14</sup>) made up of two adiabatic processes (compression and expansion) and two isobaric processes (heating and cooling).

<sup>14</sup> Considering air, a perfect gas is  $H = c_p \cdot T$  and being  $c_p$  constant  $H$  and  $T$  only differ for a scale factor, therefore the cycle has the same form on planes  $H-S$  and  $T-S$ .

As a matter of fact, in widespread plants the cooling process does not exist since these are open-cycle plants; at the end of expansion, air is released into the atmosphere.

Air, taken from the atmosphere and compressed in an axial compressor (transformation 1–2), is then sent to the combustion chamber where its temperature is increased at a constant pressure (transformation 2–3); this is followed by the expansion in the turbine (transformation 3–4) and the release into the atmosphere.

### *Specific Work and Efficiency*

Since, as already said, the open-cycle plant is an *internal combustion* plant, it is necessary to note that the cycle has a variable mass, since a given quantity of air mass is compressed in the compressor and, together with the fuel introduced in the combustion chamber, it expands in the turbine. Having defined  $\alpha$  as the ratio between the air mass and the fuel mass, and LHV the lower heating value of the fuel, it follows that:

$$Q_1 = \frac{\text{LHV}}{\alpha + 1} = c_p(T_3 - T_2) \Rightarrow \alpha = \frac{H_i}{T_3 - T_2} - 1 \quad (4.21)$$

Let's consider, as an example, the following values of the characteristic parameters:

LHV = 10,000 kcal/kg (gasoil)

$T_3 = 1,300$  K

$T_2 = 549$  K ( $T_1 = 27^\circ\text{C}$ ,  $\beta = p_2/p_1 = 9$ )

$c_p = 0.26$  (mean value between  $T_3$  and  $T_2$ ).

From (4.21) it is possible to obtain  $\alpha = 53.8$  which means that to each kg of air react with 0.0186 kg of fuel; therefore the constant mass can be approximately accepted.

Here it is recalled that compression 1–2 (1–2' in the real case) and expansion 3–4 (3–4' in the real case) originate, respectively, compression work  $L_c$  and expansion work  $L_t$ , with regard to Fig. 4.16. The efficiency of the ideal cycle<sup>15</sup> is:

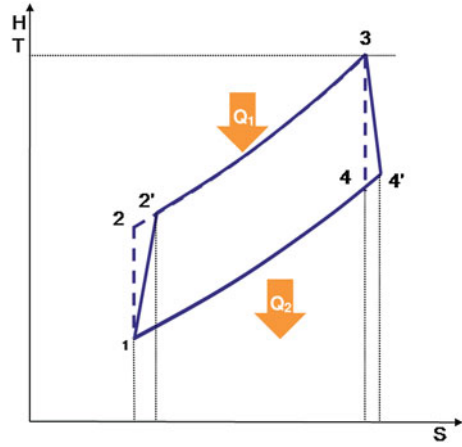
$$\begin{aligned} \eta_l &= \frac{L_t - L_c}{Q_1} = \frac{c_p(T_3 - T_4) - c_p(T_4 - T_1)}{c_p(T_3 - T_1)} \\ &= 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1 T_4 / T_1 - 1}{T_2 T_3 / T_2 - 1} \end{aligned} \quad (4.22)$$

Taking into consideration the status equations and processes, the result is:

$$\frac{T_1}{T_2} = \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} ; \quad \frac{T_4}{T_1} = \frac{v_4}{v_1}, \frac{T_3}{T_2} = \frac{v_3}{v_2}; \frac{v_3}{v_2} = \frac{v_4}{v_1} \Rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2} \quad (4.23)$$

<sup>15</sup> In the ideal cycle, the reversible isentropic compression and expansion transformations are considered.

**Fig. 4.16** Ideal (*dashed line*) and real (*continuous line*) Joule cycle



Subsequently, since the compression ratio  $\beta$  and the parameter  $\varepsilon$  are defined as follows:

$$\beta = \frac{p_2}{p_1} \quad (4.24)$$

$$\frac{k-1}{k} = \varepsilon \quad (4.25)$$

By replacing (4.23), (4.24) and (4.25) in (4.22), the ideal efficiency  $\eta_i$  is obtained:

$$\eta_i = 1 - \frac{1}{\beta^\varepsilon} \quad (4.26)$$

Indicating with  $\eta_c$  the *efficiency of the compressor* and with  $\eta_t$  the *efficiency of the turbine*, the real specific work of cycle  $L_r$  is:

$$L_r = L_{tr} - L_{cr} = c_p \eta_t (T_3 - T_4) - \frac{c_p}{\eta_c} (T_2 - T_1) \quad (4.27)$$

After adimensionalising, dividing by  $c_p T_3$  ( $T_3$  is fixed at a maximum value for technological reasons), and considering

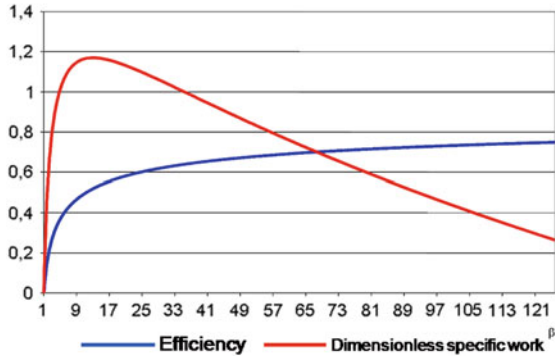
$$\tau = \frac{T_3}{T_1} \quad (4.28)$$

through a procedure analogous to the previous one, it is possible to obtain:

$$\frac{L_r}{c_p T_1} = \eta_t \left( \tau - \frac{\tau}{\beta^\varepsilon} \right) - \frac{1}{\eta_c} (\beta^\varepsilon - 1) \quad (4.29)$$

The trends in efficiency and in the specific work according to  $\beta$  are shown in Fig. 4.17. The respective maximum values are obtained for different values of the

**Fig. 4.17** Specific work and efficiency of the gas cycle according to the compression ratio

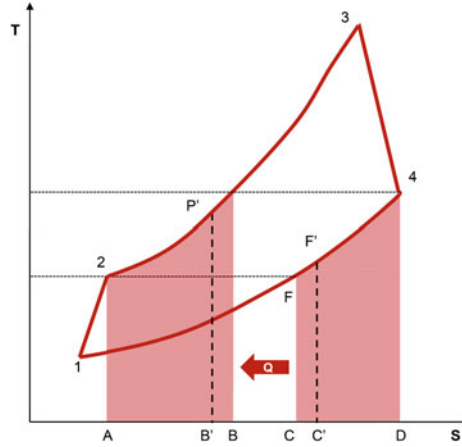
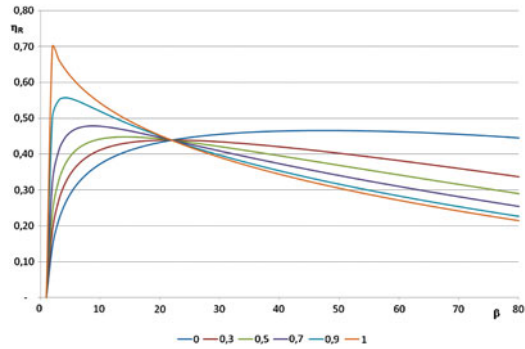


compression ratio. Assuming  $T_3 = 1.300$  K,  $T_1 = 300$  K,  $k = 1.38$ ,  $\eta_c = 0.88$  and  $\eta_t = 0.9$ , the maximum specific work is obtained with  $\beta = 8.4$  ( $L = 1.0231$  kJ/kg and  $\eta = 0.3454$ ), whereas the maximum efficiency is obtained with  $\beta = 20$  ( $\eta = 0.388$  and  $L = 859.4$  kJ/kg). Considering that the trend of the efficiency curve near the maximum level is flatter than the specific work, intermediate values of the compression ratio are adopted, although closer to the optimum of the specific work:  $\beta = 10 \div 12$  (with  $\beta = 12$  it is possible to obtain  $\eta = 0.3716$  and  $L = 996.3$  kJ/kg).

As already mentioned, the maximum temperature of the cycle is imposed by technological factors that concern the resistance of the blades of the turbine to high temperatures: mechanical strength, creep, corrosion. By using cooled blades, the maximum temperature presently achievable is 1,300–1,350°C. With  $T_3 = 1,350^\circ\text{C}$  the maximum specific work is obtained with  $\beta = 12.9$  ( $L = 2,147.4$  kJ/kg and  $\eta = 0.4088$ ) whereas the maximum efficiency is obtained with  $\beta = 38$  ( $\eta = 0.4605$  and  $L = 1,777.8$  kJ/kg).

### Thermal Regeneration

With the values of maximum temperature of cycle  $T_3$  and of the compression ratio  $\beta$  mentioned above, it is possible to obtain a temperature  $T_2 \approx 320^\circ\text{C}$  at the end of the compression and  $T_4' \approx 500^\circ\text{C}$  at the end of the expansion. Having considered  $T_4' > T_2'$  thermal regeneration is therefore possible. It consists in using the heat of flue gases at the discharge of the turbine (corresponding to area CF4'D in Fig. 4.18) to preheat the air before accessing the combustion chamber. Taking into consideration the thermal gradients that are necessary for thermal exchange, it is not possible to perform a “complete” regeneration; the heat that is actually usable to preheat the air is the one corresponding to area C'F'4'D in Fig. 4.18 that will take the air before accessing the combustion chamber at temperature TP' (in the ideal case of complete regeneration, the temperature TP would be reached). In this connection the *degree of regeneration*  $R$  is defined:

**Fig. 4.18** Joule cycle with thermal regeneration**Fig. 4.19** Gas cycle efficiency regenerated according to the compression ratio, on the basis of some values of the degree of regeneration

$$R = \frac{c_c (T'_4 - T'_F)}{c_p (T'_4 - T_F)} \quad (4.30)$$

The quantities of heat  $Q_1$  and  $Q_2$  that the fluid exchanges with the outside become:

$$Q_{1R} = c_p (T_3 - T'_4) + (1 - R) c_p (T'_4 - T'_2) \quad (4.31)$$

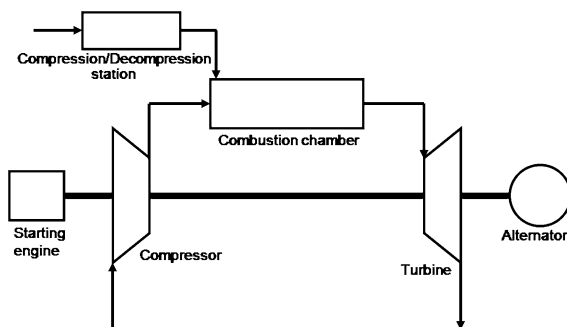
$$Q_{2R} = c_p (T'_2 - T_1) + (1 - R) c_p (T'_4 - T'_2) \quad (4.32)$$

Consequently, the efficiency, according to the characteristic parameters and to the degree of regeneration, is:

$$\eta_R = \frac{1}{\eta_c \eta_t \left(1 - \frac{1}{\beta^{\frac{1}{\gamma}}}\right) - (1 - R) \left[ \eta_t \left(1 - \frac{1}{\beta^{\frac{1}{\gamma}}}\right) - 1 + \frac{1}{\tau} \left( \frac{\beta^{\frac{1}{\gamma}} - 1}{\eta_c} + 1 \right) \right]} \quad (4.33)$$

The efficiency trend is plotted in Fig. 4.19 against  $\beta$  by varying  $R$ . As the degree of regeneration increases, also the maximum value of efficiency increases, and that

**Fig. 4.20** Scheme of an open-cycle gas plant



value is obtained for lower values of  $\beta$ . As a matter of fact too low compression ratios would penalise the specific work; for this reason, also considering that costs and size of heat exchangers increase as the degree of regeneration increases, values of  $R$  not too high are adopted, that is: 70–75% (with  $\beta = 8$ ;  $R = 0.7$   $\eta_R = 0.4189$ , with  $R = 0.8$   $\eta_R = 0.4332$ , with  $R = 0.9$   $\eta_R = 0.4486$ ). Regeneration entails the presence of a heat exchanger that would otherwise be absent in gas plants.

### *The Open-Cycle System*

Since open-cycle gas turbine plants are internal combustion systems, combustion products enter into contact with the blades of turbines; this prevents the use of “poor” fuels. Whatever the fuel used, there are two types of limits of tolerability of “contaminants”: **solid particles** that exceed some sizes and cause *erosion*, and **chemical contaminants** (vanadium, sodium, potassium, lead, nickel, calcium) that cause *corrosion*. The problem of corrosion and erosion of turbine blades remains in any case among the most severe ones for these systems.

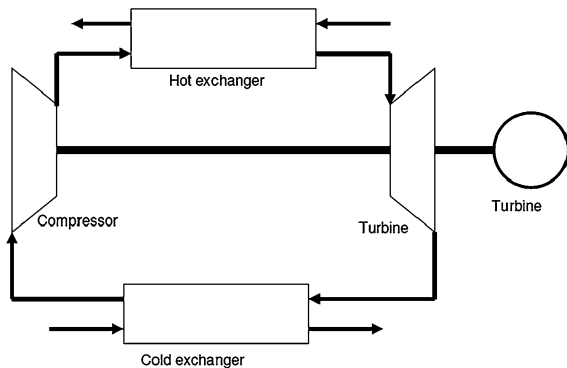
One of the attractive peculiarities of these plants is their relatively simple construction. In its simplest form, the plan of the system is shown in Fig. 4.20.

The turbine, the compressor and the alternator are assembled on the same shaft: the compressor and the alternator are operated by the turbine. In order to be injected in the combustion chamber, the fuel must be at a given pressure, normally amounting to nearly 20 bar.<sup>16</sup> The pressure at which gas is supplied varies according to the type of gas distribution network; in any case, there is usually no guarantee of a constant pressure of supply.

In the decompression station, gas decompression usually takes place (normally the supply pressure is nearly 35 bar) or, when the supply pressure drops below

<sup>16</sup> At the usual values of the compression ratio, nearly  $\beta = 12$ , the air is in a combustion chamber at the pressure of nearly 12 bar. In those cases in which high compression ratio values are adopted,  $\beta = 30$ , obviously a higher pressure for natural gas, nearly 35 bar, is necessary.

**Fig. 4.21** Scheme of a closed-cycle gas plant



some given values, a compression is performed, hence guaranteeing a constant pressure at the entry point of the combustion chamber.

At the starting of the plant, the turbine is boosted by a suitable starting engine (usually a Diesel one) that feeds it until fuel supply begins, and the ignition with suitable sparking plugs follows. Subsequently, the fuel capacity is increased according to a well-defined time law, in order to avoid thermal overloads. However, any start-up causes a stress to the plant that for the effects of ageing, costs several hours of operation at full capacity.

### *The Closed-Cycle System*

As already said, in general the plant is an *open-cycle system*. It is however possible, as in the case of gas power plants, to implement the *closed-cycle system* (Fig. 4.21). This entails undeniable advantages as far as the cycle efficiency is concerned:

- By regulating the pressure at the entry of the compressor, and therefore the flow rate, it is possible to have a *wide variation of the load at a rather constant efficiency*;
- There is the possibility of *choosing the working fluid* with convenient physical characteristics;
- It is possible to work, given the same compression ratio, with pressurised fluid, at a higher average pressure of the cycle, and therefore with a *higher specific work* given the same other electric parameters;
- The system would be an external combustion plant, and therefore the fluid enters the turbine “clean”, sharply reducing the problems of blade corrosion, and whatever type of fuel could be used.

On the other hand, in the closed-cycle plant, two *heat exchangers* are necessary—one hot and one cold—that were not present in the open-cycle, and therefore the plant is *far more complex and more expensive*. Furthermore, a certain availability of refrigerated water for the cool exchanger is needed, necessary in the open-cycle solution. Considering that the system simplicity is among the main

strengths of turbogas systems, it is easy to understand why almost all of them are open-cycle. For the same reason, also the convenience of thermal regeneration must be evaluated for each single system at the moment of construction.

### *Further Improvements*

Further measures to improve the performance of turbogas plants have been studied. Besides the already-mentioned thermal regeneration, there are two main improvements introduced:

- *Intercooled compression*
- *Fractioned expansion with reheating.*

### *Power Regulation*

The regulation of the power supplied occurs by varying the initial expansion temperature  $T_3$  acting on the fuel flow rate.<sup>17</sup>

Having considered that the conditions of the fluid vary, and since the rotation speed must remain constant (at least in case of electric energy production, to maintain grid frequency synchronous speed), the efficiency of the turbine, and therefore of the cycle, heavily decreases while departing from the conditions provided for in the plan. However, taking also into account that around 2/3 of the power supplied by the turbine are absorbed by the compressor and nearly 1/3 by the alternator, and that the fluid conditions at the beginning and at the end of the compression do not vary (therefore the power absorbed by the compressor remains unchanged), the decrease in the power supplied by the turbine is highly lower than the reduction of electric power that is intended to be obtained.<sup>18</sup> This allows rather wide regulations of the electric power supplied without excessively damaging efficiency.

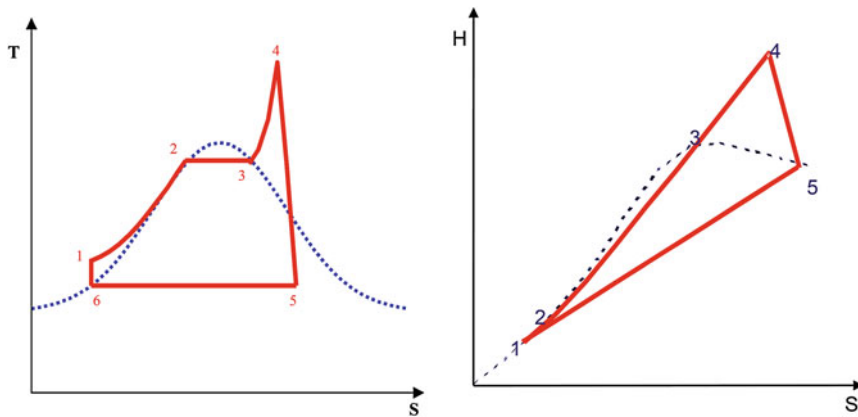
A plant solution that allows regulations of the power supplied with limited decrease of efficiency is represented by *two-axle plants*. In these plants there are two different shafts: one moves the alternator, the other moves the compressor. Obviously, a turbine must be mounted on each shaft, and therefore *expansion* must be *divided* into two machines with power ratios produced approximately as 2/3 (for the compressor) and 1/3 (for the alternator).

In this way the rotation speed of the compressor is not related to the one of the alternator, and it is possible to assign to the compressor, as the load varies, the speed that allows the maximum efficiency for that load value. The two turbines can operate either in series or in parallel.

<sup>17</sup> From (4.21) it is readily evident that by decreasing the fuel flow rate,  $T_3$  decreases.

<sup>18</sup> For instance, to halve the electric power supplied, it is necessary to bring the power supplied by the turbine at nearly 83% of the nominal value.





**Fig. 4.22** Hirn cycle on the entropic ( $T$ - $S$ ) and on the enthalpic level ( $H$ - $S$ )

### General Characteristics

The considerable technological development of gas turbines in the last decades, with the introduction of the several improvements mentioned above, entailed huge increases in the efficiency of gas plants: from 25–27% during the 1970s to 32–35% of modern plants. A peculiar characteristic of these plants is their significant *flexibility*; *very short transients* (from the still position, the plant reaches the maximum steady-state condition in a few tens of minutes) allow to quickly adapt the power supplied to the demand. These characteristics make it suitable to cover the top side of the load diagram, that is to say to provide the power requested by the grid in the periods of highest consumption. In a plant there are several turbogas groups; the power supplied is regulated by acting on the number of groups operated simultaneously besides regulating the supply of each of them in an interval that ranges from the operation at full capacity to 50% of the nominal power. The hours of operation per year are 4,000–4,500. Compared to steam plants, gas plants generally have a lower power, from less than hundred of kW<sub>e</sub>, to some hundreds to MW<sub>e</sub>.

#### 4.2.3.2 Steam Power Plants

##### *Thermodynamic Cycle*

The basic reference thermodynamic cycle is the Hirn Cycle (Fig. 4.22) envisaging two isothermobaric (water evaporation (2–3) and vapour condensation (3–6)), one isobaric (steam superheating) and two adiabatic (water compression (6–1) and steam expansion (4–5)) transformations (3–4).

Water evaporation occurs in the steam generator. In a first phase (economiser) water is brought to temperature  $T_2$ ; this process is obtained by recovering the

residual heat (transformation 1–2). In the second phase (vapouriser) the evaporation occurs by exploiting the heat produced in the burner through combustion (transformation 2–3) and finally the steam superheating occurs in the superheater up to the maximum temperature allowed (transformation 3–4). At this point, saturated and superheated steam expands in the turbine (transformation 4–5) and reaches the condenser. Here, at constant pressure and temperature, by exchanging heat with the cooling water, it condenses (transformation 5–6). Pumps bring water back to the steam generator and increase its pressure (transformation 6–1).

As regards Fig. 4.22, the efficiency and the specific work of the cycle are, respectively:

$$\eta = 1 - \frac{H_5 - H_1}{H_4 - H_1} \quad (4.34)$$

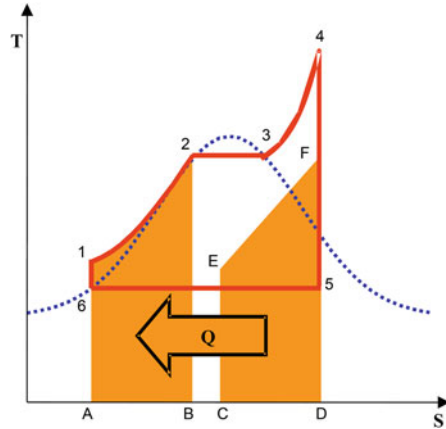
$$L = H_4 - H_5 \quad (4.35)$$

In a steam power plant, in order to improve efficiency, it is convenient that condensation takes place at the lowest possible pressure. The reason for the importance of a vacuum pushed in the condenser is that work  $\int dp/\rho$  is higher, given the same  $\Delta p$ , with low values of density  $\rho$ , namely with low pressures. Being steam saturated, pressure depends on temperature; therefore the pressure inside of the condenser is determined by the temperature of the refrigerant: normally working temperature is around 35°C and therefore 0.05 bar is the working pressure. In the condenser, besides condensation, steam outgassing occurs through extractors connected to the coldest areas. The choice of outgassing in the condenser is due to the fact that at the conditions therein existing, air solubility in water and air density is more than double than dry saturated steam, and therefore the quantity of steam inevitably removed together with air will be limited.

Once the conditions at the condenser are set, the cycle performance depends on the fluid conditions at the outlet of the steam generator. The search for optimal conditions is carried out by setting in advance the superheating temperature (maximum temperature of the cycle): this is set as a compromise between thermodynamic needs (Carnot effect) that demand values as high as possible, whereas technical–economic reasons impose some limitations. In consideration of these elements, the superheating temperature is typically set at 550–600°C. At these temperatures, the pressures corresponding to optimal conditions exceed the critical pressure of water (218 bar); as a matter of fact, although supercritical plants exist (in the case of large-size groups), in the vast majority of cases the outlet pressure of the steam generator is 100–180 bar. This is because the *efficiency gain*  $\Delta\eta/\eta$  decreases as pressure increases, and it is therefore necessary to evaluate the convenience in pushing maximum pressure beyond some values to the detriment of costs, safety and easiness of management.

From the steam conditions mentioned above, an increase in the specific volume of over 1,000 times is reached during the duty cycle. For this reason turbines are divided into three bodies (high, medium, and low pressure ones) so that a limited

**Fig. 4.23** Hirn cycle with thermal regeneration



increase of the specific volume occurs in each of them. The low-pressure bodies are often divided into several elements (usually two) placed in parallel.

The cycle described until now is the reference basic cycle, to which some typical changes are made in order to improve its efficiency, mainly thermal regeneration and repeated superheating.

### Thermal Regeneration

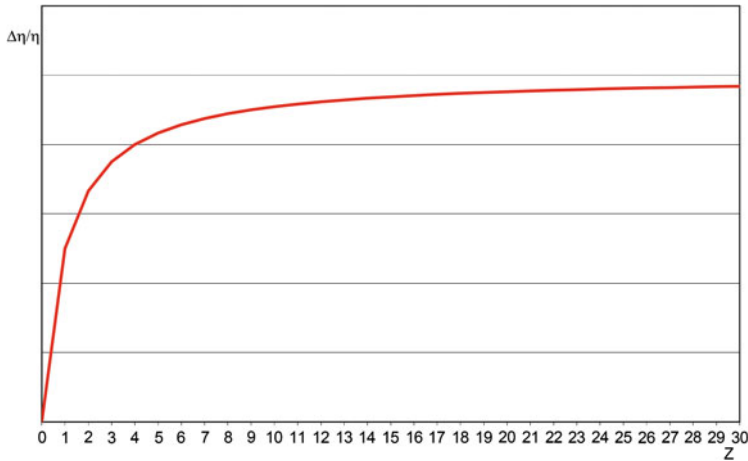
Thermal regeneration consists of using the heat,  $Q$ , available during the steam-condensation before the end of expansion (CEFD area in Fig. 4.23), in order to preheat the water coming from the condenser before entering the steam generator (area A12B).

Thermal regeneration through heat subtraction, however, is not convenient since the steam fraction at the end of expansion (point F) would be too low, endangering the integrity of the turbine or, at least, its efficiency.

The same regenerative effect can be *obtained by removing steam from expansion rather than heat* and mixing such steam with the water to be preheated. In this way the steam removed directly gives its thermal content to the liquid during the heating phase, whereas the steam in the turbine continues its expansion undisturbed. In fact, practical thermal regeneration takes place through a given number of bled-steam during expansion: the number and the position of this bleeding is fixed according to technical-economic optimisation criteria.

The regeneration degree  $R$  is defined as the ratio between enthalpy variation by mass unit conferred to the liquid through regeneration ( $h_{x1} - h_0$ ) and the total one ( $h_1 - h_0$ ):

$$R = \frac{h_{x1} - h_0}{h_1 - h_0} = \frac{h_{x1} - h_0}{\lambda} \quad (4.36)$$



**Fig. 4.24** Efficiency gain according to the number of bleedings

where:

$$\lambda = h_1 - h_0 \quad (4.37)$$

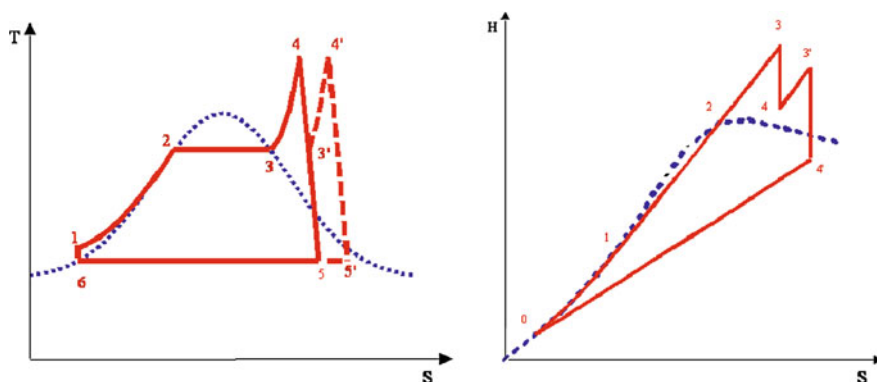
Indicating with  $z$  the number of steam bleedings, the maximum efficiency value is obtained for:

$$R = \frac{z}{z + 1} \quad (4.38)$$

With these assumptions, the efficiency increase ( $\Delta\eta/\eta$ ) is plotted against  $z$  in Fig. 4.24. As  $z$  increases, the efficiency gain increases to a lower rate; besides a given value it is not convenient anymore to add other bleedings, hence further complicating the plant without a valuable increment of efficiency increase. The value of  $z$  for large installed powers is 8–10.

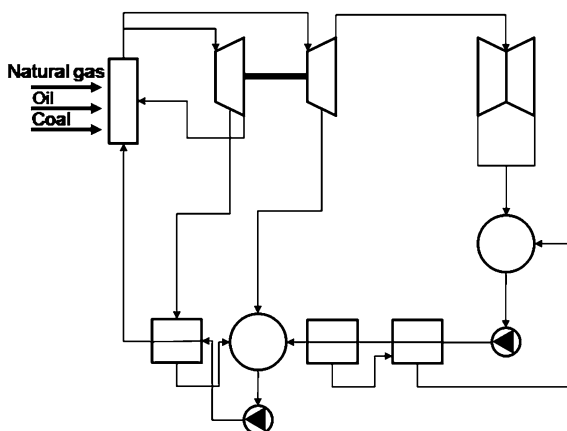
#### *Repeated Superheating (Reheating)*

In the past, the low superheating temperatures as well as the other high pressures for the optimisation of specific work and efficiency, led to wet steam, with too low steam fractions at the end of the expansion phase and the presence of water was an erosion cause for the turbine blades. To prevent this, the procedure of repeated superheating was developed. After expansion 40–30 (Fig. 4.25), steam is superheated at a constant pressure (transformation 30–40) up to a temperature equal to or slightly lower than  $T_4$ . Although developed to solve the problems related to a too low steam fraction at the end of expansion, the double superheating has advantages also from the merely thermodynamic viewpoint: by increasing the portion of heat released at high temperatures, on the basis of the multiple-source theory, overall efficiency increases. For this reason, although present superheating



**Fig. 4.25** Steam cycle with double superheating on the anthropic and enthalpic level

**Fig. 4.26** Diagram of a multifuel steam plant with double superheating



temperatures do not entail any low-fraction problems, the double superheating remains a very widespread practice.

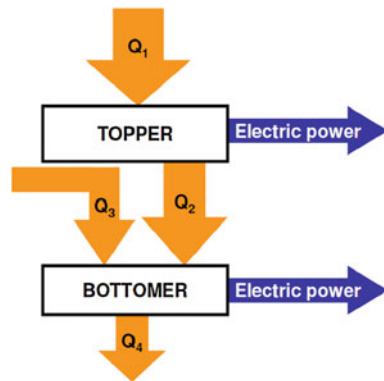
## The Power Plant

Figure 4.26 shows the diagram of a steam power plant with double superheating and bled-steam (with mixing  $S$ ).

In steam plants it is possible to use whatever type of fuel, including nuclear one; the most commonly used are *fuel oil*, *coal* and *natural gas*. Modern plants are *multifuel*, that is to say they have a boiler whose combustion systems allow to use different fuels without distinction. This solution offers a huge flexibility that allows to vary the fuel used according to market needs or to product availability.

Heat exchange between bled-steam and the liquid to reheat can take place in *mixture regenerators* or in *surface regenerators*.

**Fig. 4.27** Diagram of the combined plant



Mixture regenerators, although efficient from the thermal exchange viewpoint, show, however, different plant disadvantages. They are bulky and heavy, but most of all require the *accelerator pump*  $P_R$ , necessary to introduce the liquid—in the form of cold condensation—in the downstream regenerator, which is at a higher pressure. Therefore, by using mixture regenerators,  $z$  accelerator pumps (as many as bleedings) would be necessary, besides sump pumps; the capacity of these pumps would be close to the one feeding the steam generator.

To avoid these complications, *surface regenerators* are used, in which thermal exchange takes place through the walls of the tube bundles containing the water to be heated and externally lapped by the condensing steam. In these regenerators, the two areas between which heat exchange takes place are entirely independent and therefore nothing influences the pressures therein existing. It follows that a single pump can push the main condensation to the various regenerators, in a cascading distribution.

The condensations of the bled-steam flows can be sent from each regenerator to the one immediately upstream (through a flow-rate regulation valve), or to the regenerator downstream (at a higher pressure) through a pump that should only process the flow-rate of condensation relating to the bled-steam, that is to say a very limited capacity, differently from the case of mixture regenerators. The solution normally adopted is the one that provides for condensation to be sent to the upstream regenerator.

Despite of the advantages of surface regenerators, a mixture regenerator is always included in plants. The fact that it entails the insertion of a pump is not a problem, since it takes on the function of feed pump, in order to allow the feed pump and the sump pump to share the task of taking the liquid from the very low pressure in the condenser to the very high pressure in the boiler.

Furthermore, the mixture regenerator, *if operating in balanced conditions*, brilliantly performs the task of degasser, which is very important in steam plants, especially the high-power ones, and that condensers alone cannot satisfactorily perform. For this reason, the pressure in the only mixture regenerator (degasser) in the plant, performs its role in terms of balancing the condensation temperature of

the bled-steam. Such pressure must exceed atmospheric value to favour the spontaneous outburst of bases from the water-steam system.

### *The Cooling Circuit of the Condenser*

If a sufficient water flow is available, the circuit is open. With this type of circuit, water—after the thermal exchange—is reintroduced in the water body of origin. Conversely, if the continuous water flow available is not sufficient, then the closed circuit is used, where the cooling water, after the thermal exchange, is cooled in suitable *cooling towers*.

In the cooling towers, a close contact is established between water and an airflow; the latter absorbs heat both by convention and through the increase of its fraction (the outlet air fraction is close to one unit), following the evaporation of a small portion of cooled water.

Water is injected at a certain height of the tower and dropped on a stacking of elements in plastic, wood or zinc-coated plate, in order to be dispersed in drops or in thin layers, increasing in this way the surface of contact with the air, and subsequently be collected in a tank of cold water. On the contrary, the air comes from the bottom, covers the tower up to the top, meets water as a counter flow and outgoes from the top.

*Air circulation can be either natural or forced.*

In natural-draught towers, the air flows due to a chimney effect, which implies huge heights and large sections; the upper dimpling of the tower causes a decrease in speed and in air temperature and, therefore, the condensation of a part of water contained in it, with subsequent drop and recovery. Air speed in general does not exceed 3 m/s and “rain density” is about  $0.001 \text{ m}^3/\text{m}^2 \text{ s}$ .

In forced-draught towers, the air is set in motion by fans; this allows to have far smaller towers, although with higher construction and operating cost due to the energy consumption of fans and system maintenance. In this case air speed can exceed 10 m/s whereas “rain density” amounts to nearly  $0.003 \text{ m}^3/\text{m}^2 \text{ s}$ .

As already said, a fraction of refrigerated water evaporates: water consumption  $G$  due to evaporation, having defined  $x_2$  and  $x_1$  the values of the input and outlet air fraction, respectively, and  $G_a$  the airflow rate, is given by

$$G = G_a(x_2 - x_1) \quad (4.39)$$

and generally amounts to a very limited percentage of the flow of the treated water. However, the flow of the restoration water must be higher than the one consumed due to evaporation, because the subsequent recycles would unacceptably increase salt concentration in water, and it is therefore necessary to operate some draining that must then be offset.

The flow of water necessary for steam condensation is remarkable. By considering, for instance, the following conditions at the beginning and at the end of the expansion:

- Input steam in the turbine  $p = 150$  bar and  $T = 540^\circ\text{C}$
- Steam to the condenser  $p = 0.05$  bar and  $T = 33^\circ\text{C}$
- Expansion efficiency in turbines: 0.86.

It is possible to calculate that, in order to produce 1 kWh, nearly 3 kg of steam are necessary, that is to say to provide a power of 1 kW a steam flow of nearly 3 kg/h is necessary.

In a 1,200 MW power plant, typically made up of four groups of 300 MW the steam flow for one group amounts to 250 kg/s. The balancing equation of heat exchange between cooling water and steam, where  $m_a$  is the flow rate of water,  $c$  its specific heat, assuming  $\Delta T = 15^\circ\text{C}$  (to increase higher temperature excessively large exchanging surfaces would be necessary) and  $\Delta H_c = 2.440$  kJ/kg the steam condensation heat is:

$$m_v \Delta H_c = m_a c \Delta T \quad (4.40)$$

Therefore:

$$m_a = \frac{m_v \Delta H_c}{c \cdot \Delta T} \cong 9.720 \text{ kg/s} \quad (4.41)$$

to which corresponds a volume flow rate of nearly  $10 \text{ m}^3/\text{s}$  and therefore an overall flow rate for the four groups of  $40 \text{ m}^3/\text{s}$ .

### *General Characteristics*

Steam power plants show rather high efficiencies which in the best possible cases reach 46%; load regulation is possible only within given limits, beyond which efficiency drastically decreases and transients are deleterious for the plant, since they negatively impact its lifetime. And in any case the thermal energy of the large fluid mass involved would not allow the quick response that is conversely possible in turbogas power plants. For these reasons, steam plants are used for the production of basic electric power, that is to say cover the lower part of the load diagram, in large-size plants often (exceeding 1,000 MW), and have a high number of hours of full load equivalent operation of 6,000–6,500 h/year, and even beyond.

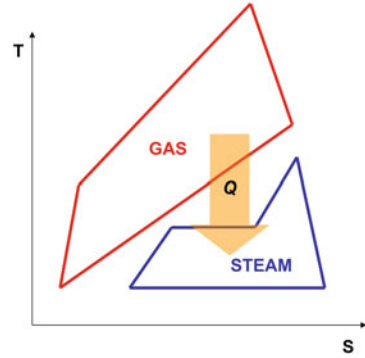
A plant is usually made up of several groups, whose size ranges between 300 and 660 MW.

#### **4.2.3.3 Combined Cycle Power Plants**

The efficiency of thermodynamic cycles increases as the ratio between maximum and minimum operating temperature of the cycle increases. In the cycles of steam and gas thermoelectric plants, there are thresholds for these temperatures: in steam plants the maximum temperature of the cycle is limited by the relatively low value of the critical temperature of water ( $374.1^\circ\text{C}$ ), whereas in gas plants this limit concerns the temperature at the exhaust of the turbine that is imposed, after setting



**Fig. 4.28** Gas–steam combined cycle



the initial expansion temperature and the compression ratio, by room temperature. Since the two limits are complementary, it is possible to combine two cycles so that the exhaust heat of the gas cycle represents the source of heat, or part of it, for the steam cycle. From the thermodynamic point of view, the gas plant is overlapped (*topper*) to the steam plant (*bottomer*); the maximum and minimum temperatures of the cycle “deriving” from the combination of the two simple cycles, are, respectively, the maximum temperature of the gas cycle, exceeding 1,000°C, and the minimum temperature of the steam cycle, nearly 30°C (Fig. 4.28).

The efficiency of the combined cycle depends on the efficiencies of both cycles and is, in any case, higher than each of them. Figure 4.28, having defined  $\eta_c$ ,  $\eta_g$  and  $\eta_v$  the efficiencies of the combined cycle, of the gas cycle and of the steam cycle respectively, it follows that:

$$\eta_c = 1 - \frac{Q_4}{Q_1 + Q_3} \Rightarrow 1 - \eta_c = \frac{Q_4}{Q_1 + Q_3} \quad (4.42)$$

$$\eta_v = 1 - \frac{Q_4}{Q_3 + Q_2} \Rightarrow 1 - \eta_v = \frac{Q_4}{Q_3 + Q_2} \quad (4.43)$$

$$\eta_g = 1 - \frac{Q_2}{Q_1} \Rightarrow 1 - \eta_g = \frac{Q_2}{Q_1} \quad (4.44)$$

Assuming:

$$\mu = \frac{Q_1 + Q_3}{Q_1}, \quad (4.45)$$

replacing (4.45), (4.44) and (4.43) in (4.42) it is possible to obtain:

$$1 - \eta_c = \frac{Q_4}{\mu \cdot Q_1} = \frac{Q_4}{Q_2 + Q_3} \frac{Q_2 + Q_3}{\mu \cdot Q_1} = (1 - \eta_v) \frac{Q_2 + Q_3}{\mu \cdot Q_1} \quad (4.46)$$

Being:

$$\frac{1}{\mu} \left( \frac{Q_2 + Q_3}{Q_1} \right) = \frac{1}{\mu} \left( 1 - \eta_g + \frac{Q_3}{Q_1} \right) = 1 - \frac{\eta_g}{\mu}, \quad (4.47)$$

replacing (4.47) in (4.46) it follows:

$$1 - \eta_c = (1 - \eta_v) \left( 1 - \frac{\eta_g}{\mu} \right), \quad (4.48)$$

from which the efficiency of the combined plant is derived:

$$\eta_c = \eta_v + \frac{\eta_g}{\mu} (1 - \eta_v) \quad (4.49)$$

If  $Q_3 = 0$  and  $\mu = 1$ , the efficiency of the combined cycle becomes:

$$\eta_c = \eta_v + \eta_g - \eta_v \eta_g \quad (4.50)$$

Equation 4.50, assuming constant  $\eta_v$  and  $\eta_g$ , is the maximum value obtainable in (4.49).

Two fundamental solutions are possible for gas-steam combined plants: *with* or *without the afterburning* of gas turbine exhaust gases.

The efficiency of combined cycles depends on the efficiency of component cycles according to (4.49); in the last few years, the development of gas turbine technologies allowed huge increases in the efficiency of combined plants, presently reaching values exceeding 55%.

The high efficiency, as well as the use of a “clean” fuel as methane, allow to reduce  $\text{NO}_x$ ,  $\text{SO}_x$ ,  $\text{CO}$ , and  $\text{CO}_2$  emissions, as well as particulate emission abatement compared to conventional solutions.

#### 4.2.3.4 Fuel Cells

The energy conversion systems analysed above, involving the conversion of chemical energy into electric power, perform a thermodynamic conversion. However, there are converters based on electrochemical principles often more efficient and effective than the former; they are described in this section.

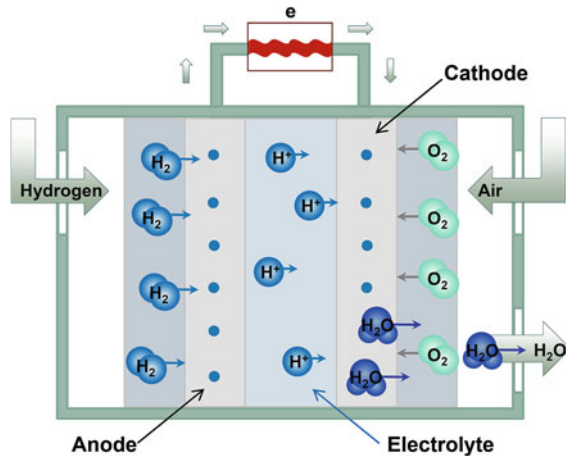
##### Overview

The origin of fuel cells date back to 1839, the year in which the British William Grove generated electricity from a cell containing phosphoric acid, delimited by two electrodes reached by hydrogen and oxygen, respectively.

The basic principle of operation is the following: the cell is made up of two electrodes of porous material, separated by an electrolyte. Electrodes act as catalytic sites for the breakdown of reagents into ions; the electrolyte conducts ions preventing the passage of electricity, conveyed to an external circuit on the tips of the two electrodes.

Fuel cells are electrochemical systems that directly convert the chemical energy of a fuel (usually hydrogen) into electric power, according to an isothermal and

**Fig. 4.29** Diagram of fuel cells



isobaric process. Therefore, they eliminate the irreversibility associated to combustion, without considering the passage through the stage of thermal energy, and allow to depart from the maximum efficiency threshold of thermal machines, represented by the Carnot efficiency.

A distinctive feature of the operation of a fuel cell, compared to the conventional conversion of chemical energy through an oxidation reaction, is the fact that in this device both fuel and oxidiser are combined in the form of ions not directly but *through an electrolytic path*. In this case reagents are external to the cell (differently from what happens in a normal electric battery); on the other hand, neither electrodes nor the electrolyte are consumed in the complex of reaction.

In theory, any oxidation and reduction can be at the basis of a fuel cell. It is fundamental, however, that a ion reaction occurs, and that the transportation of electric charges occur rapidly.

### *Operating Principle of Fuel Cells*

The cell is made up of two electrodes (anode and cathode) in a porous material, separated by an electrolyte (Fig. 4.29). Electrodes act as catalytic sites for reactions, breaking down and consuming the fuel and the oxidiser. Always within the electrodes, the product of the reaction between fuel and oxidiser is formed, and a difference in voltage arises which can be exploited by an external circuit. The electrolyte has the task of conducting the ions produced by a reaction and consumed by the other, closing the electric circuit. The cathode stores a superficial layer of negative charges, and they attract the positive ions from the electrolyte, producing an electric double layer. At the same time, the loss of electrons by the anode produces a layer of positive charges, which attracts the negative ions from the electrolyte. The double layers increase their concentration until the potentials can prevent further reactions between the electrolyte and the fuel gases. By closing the external circuit, electrons move towards the anode to participate in the

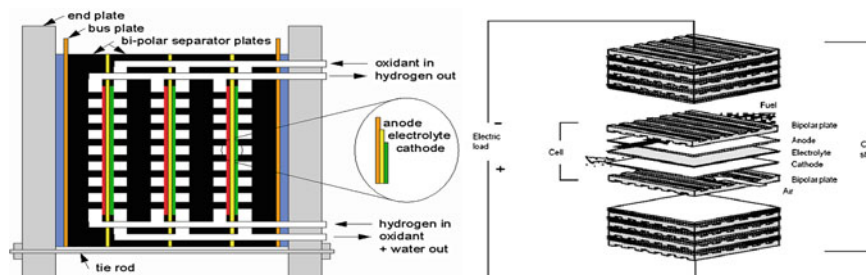
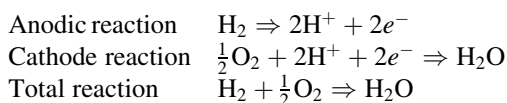


Fig. 4.30 Stack of cells

reaction; the movement of electrons makes up the electric current that, through an external load, produces work. Therefore, in this way it is possible to obtain electric work directly from the chemical process.

Electrodes act as catalytic sites for the cell reactions that mainly consume hydrogen and oxygen, with the production of water and passage of electric current in the external circuit. The electrochemical transformation is accompanied by heat production.



### The Stack

The exposed surfaces must have a sufficient area to obtain current strengths suitable to the application needs. It is possible to have the desired surfaces, by silling the cells. The stacking of cells obtained in this way forms the so-called fuel cell stack (Fig. 4.30), which represents the basis of the typical technological use of fuel cells.

### The Thermodynamics of Fuel Cells

In the analysis of the phenomena related to the operation of fuel cells, the standard charge is the one allowed by a mole of electrons; it is called “*Faraday constant*” (denoted as  $F$ ). Having considered that in a mole there are  $6.023 \times 10^{23}$  electrons and that one electron has the charge of  $1.602 \times 10^{-19}$  C, it follows:  $F = 96,485^{19}$  C/mol.

*The Faraday’s Law concerning electrolysis can be summed up as follows: in the operation of the battery, one charge of 96,485 C deposits or consumes one*

<sup>19</sup> The exact value (National Institute of Standards and Technology—2008) is  $F = 96,485.3399$  C/mol.

*gram equivalent of substance on each of the electrodes.* The weights of the substances that intervene in the reactions of electrons are linked to the charge transported ( $q$ ) according to the equation:

$$q = n \cdot z \cdot F \quad (4.51)$$

where  $n$  is the number of grams-atom or moles that react and  $z$  is the number of electrons transported by each ion.

In considering the first Law of thermodynamics in its form:

$$\Delta U = Q - L_{\text{tot}} \quad (4.52)$$

in the case of fuel cells,  $L_{\text{tot}}$  is referred both to the electric work  $L_e$  and to the expansion mechanic work,  $L_m$ . The maximum value of the electric work amounts to the product of *f.e.m.* of the cell,  $E$ , times the charge that goes through it:

$$L_e = E \cdot q \quad (4.53)$$

On the other hand, using (4.52), (4.53) can be written as follows:

$$L_e = n \cdot z \cdot F \cdot E \quad (4.54)$$

And the total work, therefore:

$$L_{\text{tot}} = p \cdot \Delta v + n \cdot z \cdot F \cdot E \quad (4.55)$$

Having considered (4.55), (4.52) becomes:

$$\Delta U = Q - p \cdot \Delta v - n \cdot z \cdot F \cdot E \quad (4.56)$$

Thus, introducing the second law of Thermodynamics:

$$\Delta U = T \cdot \Delta S - p \cdot \Delta v - n \cdot z \cdot F \cdot E \quad (4.57)$$

The reactions in the fuel cell take place at constant temperature and pressure, therefore the variation of Gibbs' free energy<sup>20</sup> ( $G$ ) and of the enthalpy<sup>21</sup> ( $H$ ) are the following:

$$\Delta G = \Delta H - T \cdot \Delta S \quad (4.58)$$

$$\Delta H = \Delta U + p \cdot \Delta v \quad (4.59)$$

By replacing (4.59) in (4.58) it follows that

$$(\Delta G)_{p,T} = \Delta U + p \cdot \Delta v - T \cdot \Delta S \quad (4.60)$$

So, having considered (4.57), it is possible to obtain:

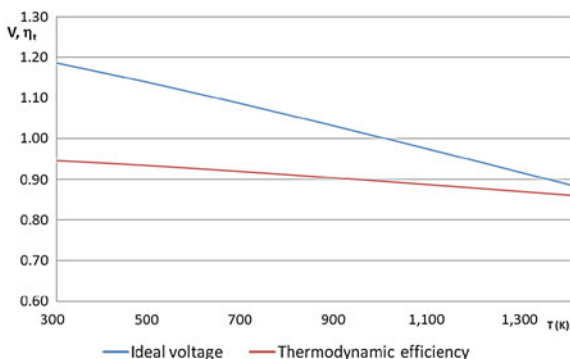
$$(\Delta G)_{p,T} = -n \cdot z \cdot F \cdot E \quad (4.61)$$

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<sup>20</sup>  $G = H - TS$ .

<sup>21</sup>  $H = U + pv$ .

**Fig. 4.31** Variation of the ideal voltage ( $V$ ) and of thermodynamic efficiency according to temperature



Equation 4.61 shows that the electric work produced by the fuel cell amounts to the decrease of Gibbs' free energy of the reaction.

With this expression it is possible to derive the maximum potential for a cell; therefore from (4.61) and (4.54) it is obtained:

$$E_0 = -\frac{\Delta G}{n \cdot z \cdot F} \quad (4.62)$$

In case hydrogen and oxygen react to form water in standard conditions<sup>22</sup> then it is possible to obtain  $E_0 = -1,186$  V.

The ideal thermodynamic efficiency (assuming the reversible transformations) is:

$$\eta_t = \frac{\Delta G}{\Delta H} \quad (4.63)$$

In the case in point, always in standard conditions,  $\eta_t = 0.9458$  is obtained.<sup>23</sup>

Gibbs' free energy and enthalpy variations depend on temperature and pressure; therefore, as they vary, both the ideal voltage (open circuit) and the ideal thermodynamic efficiency vary accordingly. Without lingering on the details of calculations, it is possible to conclude that the ideal voltage and the thermodynamic efficiency slightly increase as pressure increases (Fig. 4.31), whereas they decrease as temperature increases (Fig. 4.32).

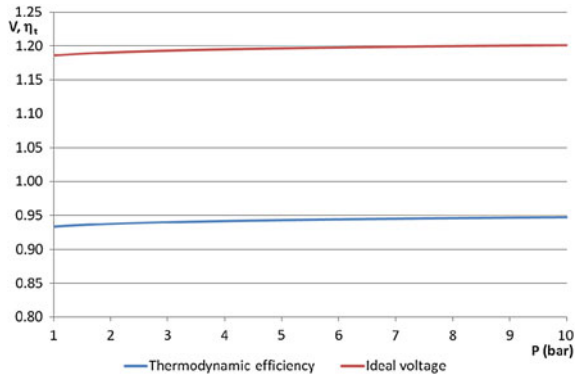
The previous reactions are obtained by considering all processes as reversible. Taking into consideration irreversibility, indicating with  $\Delta S^*$  the entropy variation in case of real transformations (irreversible), with  $\Delta S_{\text{irr}}$  the variation due to irreversibility and with  $\Delta S$  the one of reversible transformations, it follows that:

$$\Delta S^* = \Delta S_{\text{irr}} + \Delta S. \quad (4.64)$$

<sup>22</sup> The reaction  $\Delta G$  of water formation in standard conditions ( $T = 25^\circ\text{C}$  and  $p = 1$  bar) amounts to 228,888 J/mol, the number of moles ( $n$ ) involved in the reaction is 2, and the number of electrons transported by each (hydrogen) ion is 1.

<sup>23</sup> The reaction  $\Delta H$  to water formation in standard conditions amounts to 242,000 J/mol.

**Fig. 4.32** Variation of the ideal voltage ( $V$ ) and of thermodynamic efficiency according to pressure



Having considered that, according to the II Law of Thermodynamics,  $\Delta S_{\text{irr}} > 0$  (4.64) shows:

$$\Delta S^* > \Delta S \quad (4.65)$$

In the case of real transformations, (4.58) becomes:

$$\Delta G^* = \Delta H - T \cdot \Delta S^* \quad (4.66)$$

Considering (4.65) and being  $T > 0$ , then (4.66) shows:

$$\Delta G^* < \Delta G \quad (4.67)$$

Therefore, in the case of irreversible transformations, the electric work is lower. Indicating with  $V$  the closed circuit voltage<sup>24</sup> (irreversible), it follows that:

$$V < E \quad (4.68)$$

As concerns efficiency, recalling (4.67), it follows:

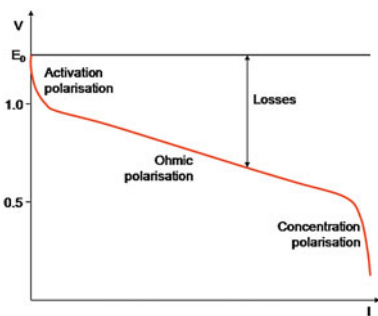
$$\eta_i^* = \frac{\Delta G^*}{\Delta H} < \eta_t \quad (4.69)$$

### Efficiency of Fuel Cells

The main cause of irreversibility of fuel cells can be identified in the heat developed by current due to the Joule effect in its passage through the electrolyte. Furthermore, irreversible phenomena occur when the circuit is closed, causing a decrease in the electric potential. These phenomena occur in three different forms: *ohmic polarisation*, due to the resistance of the electrolytic membrane at the passage of ions and the resistance of electrodes at the passage of electrons;

<sup>24</sup> The passage of current generates irreversibility; therefore it is possible to consider  $V$  as the driving force in case of irreversible transformations.

**Fig. 4.33** Effects of polarisation phenomena



*concentration polarisation*, due to insufficient porosity of electrodes and to the spreading of products; *activation polarisation*, due to the double electric layer on the surface of electrodes, which determines an activation voltage, decreasing the speed of chemical kinetics.

Therefore, although a temperature increase reduces thermodynamic efficiency, the global efficiency increases since it reduces the ohmic polarisation (increasing the ionic conductivity of the electrolyte), and concentration polarisation (improving the transportation and activation phenomena together with, improving the reaction kinetics) and generally improves the tolerance to the impurities present in gas supply. However, too high temperatures accelerate the corrosion phenomena, the problems in terms of sintering and crystallisation of catalysts, and the degradation of the electrolyte.

A pressure rise, on the contrary, increases thermodynamic efficiency and, in producing higher partial pressures of reagents, improves the phenomena of gas transportation and solubility in the electrolyte, contributing to reduce the electrolyte losses, therefore increasing overall efficiency. However, too high pressures entail problems of resistance of the different materials, and require an accurate control of differential pressures (Fig. 4.33).

The efficiency referred to is the one of the single cell; a fuel cell plant is made up of one (or several) stack(s) of cells, an inverter, the auxiliary systems (anodic and cathode supply, refrigeration, etc.). There might be a system of fuel processing as well as a heat recovery system.

As concerns the entire plant, by definition it is possible to express the efficiency of the plant,  $\eta$ , as the ratio between the useful electric power ( $P_{e,u}$ ) and the product between the mass flow rate  $\dot{m}_{\text{comb}}$  of the fuel and its lower heating value:

$$\eta = \frac{P_{e,u}}{\dot{m}_{\text{comb}} \cdot \text{LHV}} \quad (4.70)$$

Indicating with  $V_r$  and  $I_r$  the real voltage and current to the terminals of the stack(s) (4.70) becomes:

$$\eta = \frac{P_{e,u}}{V_r \cdot I_r \dot{m}_{\text{comb}} \cdot \text{LHV}} = \eta_{\text{sist}} \cdot \frac{V_r \cdot I_r}{\dot{m}_{\text{comb}} \cdot \text{LHV}}, \quad (4.71)$$



having defined the system efficiency  $\eta_{\text{sist}}$  as the ratio between the useful electric power and the one produced by the fuel cell stack(s), namely:

$$\eta_{\text{sist}} = \frac{P_{e,u}}{V_r \cdot I_r} \quad (4.72)$$

By defining the efficiency of cell  $\varepsilon$  as the ratio between the real and the ideal voltage, (4.71) can be described as follows:

$$\eta = \eta_{\text{sist}} \frac{V_r}{V_{\text{id}}} \frac{I_r}{\dot{m}_{\text{comb}} \cdot \text{LHV}_{\text{comb}}} = \eta_{\text{sist}} \cdot \varepsilon \frac{V_{\text{id}} \cdot I_c}{\dot{m}_{\text{comb}} \cdot \text{LHV}_{\text{comb}}} \quad (4.73)$$

The Faradic current ( $I_F$ ) is the current that would be in the cell according to Faraday's Law in case of absence of irreversibility and other losses, that is to say:

$$I_F = z \cdot \dot{n} \cdot F \quad (4.74)$$

where  $\dot{n}$  is the mole rate (moles/s) of hydrogen consumed at the anode.

A *Faradic* (or *current*) *efficiency* is the ratio between the real current and the Faradic one:

$$\eta_F = \frac{I_r}{I_F} = \frac{I_r}{z \cdot \dot{n} \cdot F} \quad (4.75)$$

On the basis of (4.74) and (4.75), (4.73) can be written as follows:

$$\eta = \eta_{\text{sist}} \cdot \varepsilon \frac{I_r}{z \cdot \dot{n} \cdot F} \frac{V_{\text{id}} \cdot z \cdot \dot{n} \cdot F}{\dot{m}_{\text{comb}} \cdot \text{LHV}_{\text{comb}}} = \eta_{\text{sist}} \cdot \varepsilon \cdot \eta_F \frac{V_{\text{id}} \cdot z \cdot \dot{n} \cdot F}{\dot{m}_{\text{comb}} \cdot \text{LHV}_{\text{comb}}} \quad (4.76)$$

Not all the hydrogen that reaches the anode reacts; a fraction goes to the anodic discharge. Having defined  $\dot{n}_a$  the mole rate of the anodic supply, the *hydrogen use coefficient*  $U_{\text{H}_2}$  is the ratio between the hydrogen rate consumed by the anode and the one of the anodic supply:

$$U_{\text{H}_2} = \frac{\dot{n}}{\dot{n}_a} \quad (4.77)$$

Having considered (4.77), (4.76), by multiplying and dividing by  $\dot{n}_a$  becomes:

$$\eta = \eta_{\text{sist}} \cdot \varepsilon \cdot \eta_F \cdot U_{\text{H}_2} \frac{V_{\text{id}} \cdot z \cdot F}{\dot{m}_{\text{comb}} \cdot \text{LHV}_{\text{comb}}} \dot{n}_a \quad (4.78)$$

Recalling (4.54), the molar electric work  $L_{e,\text{id}}^m$  results as:

$$L_{e,\text{id}}^m = z \cdot F \cdot V_{\text{id}} \quad (4.79)$$

Therefore, indicating as  $M_{\text{H}_2}$  the molar mass (kg/mole) of hydrogen and with  $\text{LHV}_{\text{H}_2}$  its lower heating value (per mass unit), the ideal (thermodynamic) efficiency  $\eta_{\text{id}}$  can be described as follows:

$$\eta_{\text{id}} = \frac{z \cdot F \cdot V_{\text{id}}}{M_{\text{H}_2} \cdot \text{LHV}_{\text{H}_2}} \quad (4.80)$$

Taking into account (4.80), (4.78) becomes:

$$\eta = \eta_{\text{sist}} \cdot \varepsilon \cdot \eta_F \cdot U_{\text{H}_2} \cdot \eta_{\text{id}} \cdot \frac{\dot{n}_a \cdot M_{\text{H}_2} \cdot \text{LHV}_{\text{H}_2}}{\dot{m}_{\text{comb}} \cdot \text{LHV}_{\text{comb}}} \quad (4.81)$$

having considered that the hydrogen mass rate is:

$$\dot{m}_{\text{H}_2} = \dot{n}_a \cdot M_{\text{H}_2} \cdot \text{LHV}_{\text{H}_2} \quad (4.82)$$

The efficiency of fuel treatment system is the ratio between the output and the inlet energy flow in the system itself, that is to say:

$$\eta_{\text{stc}} = \frac{\dot{m}_a \cdot \text{LHV}_{\text{H}_2}}{\dot{m}_{\text{comb}} \cdot \text{LHV}_{\text{comb}}} \quad (4.83)$$

Thus taking into account (4.82) and (4.83), the efficiency can be expressed as follows:

$$\eta = \eta_{\text{sist}} \cdot \varepsilon \cdot \eta_F \cdot U_{\text{H}_2} \cdot \eta_{\text{id}} \cdot \eta_{\text{stc}} \quad (4.84)$$

During the operation of the cell, heat will be produced due to entropy variation ( $T \Delta S$ ) and to irreversibility. So, heat production per mole of reagent can be expressed as:

$$Q = \left( \frac{T \cdot \Delta S}{n \cdot F} + \Delta V \right) \cdot I = \left( \frac{\Delta H - \Delta G}{n \cdot F} + \Delta V \right) \cdot I \quad (4.85)$$

where  $\Delta V$  is the decrease of the electric potential<sup>25</sup> due to waste phenomena and  $I$  is current. Such heat can be conveniently used for cogeneration purposes, recovering in this way the energy wasted during the operation of the fuel cells and obtaining global efficiency (electric power + heat) close to one.

Some considerations on the global efficiency of fuel cells must now be made.

As concerns the system efficiency, the useful electric power  $P_{e,u}$  can be expressed as the difference between the electric power generated by the stack and the electric power absorbed by auxiliaries. The global efficiency is:

$$\eta_{\text{sist}} = \frac{P_{e,u}}{V_r \cdot I_r} = \frac{V_r \cdot I_r - P_{e,\text{aux}}}{V_r \cdot I_r} = 1 - \frac{P_{e,\text{aux}}}{V_r \cdot I_r} \quad (4.86)$$

The electric power absorbed by auxiliaries is the one relating to pumps (for the circulation of liquid and/or humidification of cells), compressors or blowers (anodic or cathode supply): if the cell works at low pressures (close to atmospheric pressure) the supply is made by blowers, whereas if the cell works at higher pressures, compressors are necessary. The adoption of high operating pressures on the one side increases the ideal efficiency, on the other side decreases the system

<sup>25</sup>  $\Delta V = E - E \cdot \varepsilon = \frac{\Delta G}{n \cdot F} (1 - \varepsilon)$ .

efficiency, since the power absorbed by compressors is far higher (given the same flow rate) than the one absorbed by blowers.

As concerns *the hydrogen utilisation factor*, it is necessary to observe that cells must be supplied with a quantity of hydrogen always exceeding the one that effectively reacts to the anode. This because, in absence of such “excess”, and due to the unavoidably inhomogeneous distribution of hydrogen, there would be areas on the anodic surface in which hydrogen concentration would be lower than necessary for anodic reactions, and this would drastically reduce the (real) potential of the cell. In brief, the real potential of the cell increases as the excess of hydrogen increases; therefore, by increasing the surplus of hydrogen, on the one side there is a decrease in the utilisation factor  $U_{H_2}$ , whereas on the other side the efficiency of the cell  $\varepsilon$  increased. The optimal value of  $U_{H_2}$  depends on the kind of cells; it ranges between 0.75 and 0.85. Excess hydrogen can be obviously recovered and reused; in this way it is possible to increase the excess of hydrogen (and, therefore,  $\varepsilon$ ), without decreasing  $U_{H_2}$ . It is necessary to consider the expenditure for the pumping activity destined to the recovery of excess hydrogen, which decreases the system efficiency  $\eta_{\text{sist}}$ .

As concerns the Faraday efficiency, it must be observed that this is always close to one 1, as a first approximation, it is possible to consider  $\eta_F = 1$ . In case the plant is directly supplied through hydrogen (produced through other means) the efficiency of the fuel treatment system must be considered as amounting to 1.

### *Classification of Fuel Cells: the Different Technological Solutions*

Fuel cells are conventionally classified according to the type of electrolyte they contain, which determines their working temperature:

- *Polymer electrolyte membrane fuel cells (PEMFC)*, using a high proton conductivity polymer membrane as electrolyte and work at temperatures ranging between 70 and 100°C (up to 120–130°C in case of “high temperature” PEMFC); they are mostly developed for small-size generation/cogeneration and vehicles’ powertrain (1–250 kW);
- *Alkaline fuel cells (AFC)*, using an electrolyte made up of potassium hydroxide and operate at temperatures around 100–250°C (some special 250 designs operate at 25–70°C). They reached a good level of technological development, mainly for special use (military and space applications);
- *Phosphoric acid fuel cells (PAFC)*, operating at temperatures close to 200°C with an electrolyte made up of a concentrated solution of phosphoric acid. They represent the most mature technology for stationary use, for cogeneration applications in the residential and tertiary applications (100–200 kW);
- *Molten carbonate fuel cells (MCFC)*: the electrolyte is a solution of alkaline carbonates fused at the working temperature of the cell (650°C) and contained in a porous ceramic matrix; they are promising especially for the generation of electric power and cogeneration of some hundreds of kW and some dozens of MW.

**Table 4.5** Classification and characteristics of the different FC

Types of fc	Electrolyte (exchanged ions)	Temp. (°C)	Catalysts	Fuel	Oxidiser	Electric efficiency (%)
PEFC	Polymeric membrane (H +)	70–100	Pt	H <sub>2</sub> , Reformed gases	O <sub>2</sub> , aria	40–60
AFC	KOH (OH-)	60–120	Pt/Pd, Ni	Pure H <sub>2</sub>	O <sub>2</sub>	60
PAFC	Phosphoric acid (H +)	160–200	Pt	H <sub>2</sub> , Reformed gases	O <sub>2</sub> , aria	40–50
MCFC	Li and K(CO <sub>3</sub> -) carbonates	600–700	Ni	H <sub>2</sub> , Reformed gases	O <sub>2</sub> , aria	45–55
SOFC	Zirconium oxides (O-)	800–1,000	–	H <sub>2</sub> , Reformed gases	O <sub>2</sub> , aria	45–60
DMFC	Polymer membrane (H +)	90–130	Pt, alloy Pt-Ru	Methanol	O <sub>2</sub> , aria	40–60

- *Solid oxide fuel cells (SOFC)*, operating at high temperatures (about 900–1000°C) to ensure a sufficient conductivity to the electrolyte, made up of ceramic material (yttrium oxide–doped zirconium oxide); as carbonate fuel cells, they are promising especially for electric power generation and cogeneration of some kW to some dozens of MW;
- *Direct methanol fuel cell (DMFC)*, operating at temperatures between 70 and 120°C. Like PEFC, they use a polymeric membrane as electrolyte. DMFC are directly fed by methanol at the anode. Methanol is easier than pure hydrogen to store because it is liquid at ambient conditions.

The fields of application of each type of fuel cells is determined by its operating characteristics, and in particular by the working temperature and by the type of fuel used. Table 4.5 sums up the different types of fuel cells with their main characteristics and the present state of technology.

The operating temperature of the cell influences the reaction kinetics, which increases with temperature. When it is particularly high, the heat generated can be profitably used, improving the general efficiency of the production system, but it generates a series of drawbacks: thermal expansion makes the assembling of components difficult, thermal stresses require materials able to support particularly severe working conditions, the lifecycle of the cell is mostly influenced by the operating cycles, and a rather long starting time is necessary.

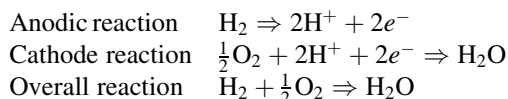
Another important aspect tied up to high temperature operating is the possibility of producing H<sub>2</sub> inside of the cell itself, starting from conventional fuels, carrying out an internal reforming. This possibility turns out into a higher simplicity of the system, since it allows to eliminate the need for an external processor and to directly supply the cell with a conventional fuel.

High-temperature fuel cells (MCFC and SOFC) are therefore suitable for applications linked to the production of electric power for stationary use with cogeneration of electricity-heat and with gas and/or steam plants.

*Polymer electrolyte membrane fuel cell:* in this type of fuel cells, the electrolyte is made up of a proton conducting polymer membrane.

The working temperature is presently limited to nearly 70–90°C by the use of polymer membranes, therefore the reaction kinetics requires the presence of catalysts (mainly platinum). However, new membranes are being developed, able to work at higher temperatures to favour both the reaction kinetics and the possible exploitation of the thermal energy produced by the cell, especially in stationary applications.

The following reactions take place in a polymer electrolyte cell:



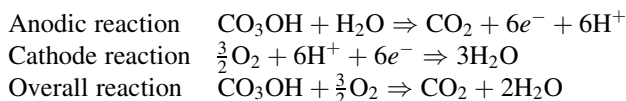
The electrolyte is made up of an ion exchange membrane, with a chlorinated sulphuric acid polymer (usually Nafion 117) with a thickness of 50–250 µm. Electrodes are made of a platinum-impregnated porous material<sup>26</sup> with a coating in Teflon (water-repellent) with a thickness of 5–50 µm.

Electrode with a porous structure are obtained by putting the catalyst on a conductive substratum. The latter consists of a layer of coal dust, bound with a polymer, on a coal tissue porous base.

The present low working temperatures also entail the use of catalysts made of noble metals (platinum), which easily poison when hydrogen is not sufficiently pure. Therefore, in the fuel processing section preceding the cell, there must be the stage of impurity elimination, CO in particular. The supply of cathodes, conversely, is generally made with air.

*Direct Methanol Fuel Cells* (DMFC) represent the latest generation of FC and can be considered as deriving from PEFC, since both use a polymer membrane as an electrolyte. However, DMFC distinguish themselves for the fuel that can be used; in fact, they can be directly powered with methanol, since they are able to electrochemically oxidise it, thanks to the use of a new class of catalysts.

The following reactions occur in a DMFC:



The possibility of using liquid methanol directly in the cell makes DMFC particularly suitable to be used in the portable electronics and mobility sectors, thanks to the remarkable simplification of the system and to the reduction of its size, also to the detriment of a lower total efficiency.

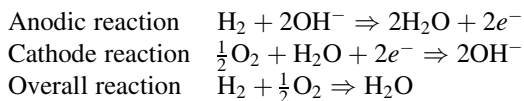
The theoretical efficiency is nearly 35–40% when operating at temperatures between 70 and 100°C; higher efficiencies can be obtained at higher temperatures.

<sup>26</sup> The platinum content for this type of cells presently amounts to nearly 0.6 mg/cm<sup>2</sup>. The electric power supplied by a cell per unit of anodic surface is nearly 0.4 W/cm<sup>2</sup>, therefore the Platinum content amounts to 1.5 g/kW. The cost of Platinum is about 40 €/g, which means that the cost of the Platinum alone contained in the anode amounts to about 60 €/kW.

The great interest for this type of technology is sided by the need to solve the still open technical problems that limit their immediate application. DMFC, in fact, still have a rapid decay in time, besides a low efficiency, and also show fuel “cross-over” problems (part of the methanol that feeds the anode crosses the electrolytic membrane and reaches the cathode by deactivating the catalyst), and furthermore the quantity of the necessary catalyst is high if compared to the one of PEFC.

*Alkaline Fuel Cell* In this type of cells, the electrolyte is liquid, and made up of an aqueous solution of potassium hydroxide (KOH) with a concentration (in weight) that varies from 30 to 85% according to the operating temperature (from usually 70 to 250°C). Electrodes are made of a carbon porous base on a mesh of Nickel with a hydrophobic coating polytetrafluoroethylene (PTFE) with a low-platinum content (0.3 mg/cm<sup>2</sup>).

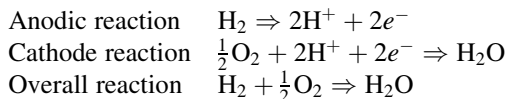
The following reactions occur in an AFC:



The circulation of the electrolyte (liquid) allows to use the electrolyte itself as a cooling substance and to empty the cell during the periods of down-time, hence avoiding the carbonisation of the cell increases its useful life. On the other hand, the corrosiveness of the electrolyte imposes the use of special materials as stainless steels and polymer materials (PVDF—*polyvinylidene fluoride*, PFA—formed by PVDF and HFP—*perfluoropropene*). These cells must be powered with very pure hydrogen and, furthermore, they show a very low tolerance to CO<sub>2</sub>, therefore it is necessary to envisage a system to remove the CO<sub>2</sub> in the air for cathode supply.

*Phosphoric Acid Fuel Cells:* in this type of cell the electrolyte (liquid) is formed by a concentrated solution (85–100%) of phosphoric acid (H<sub>3</sub>PO<sub>4</sub>) in a matrix of silicon carbide. Electrodes are made of a graphite base on which carbon catalysts with PTFE and platinum are applied (0.1 g/cm<sup>2</sup> at the anode and 0.5 g/cm<sup>2</sup> at the cathode).

The following reactions take place in a PAFC:

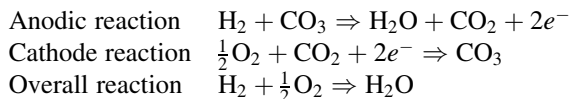


To avoid the solidification of the electrolyte, the cell must always be heated<sup>27</sup>; thanks to high operating temperatures, they show a good tolerance to impurities (nearly 1% for CO).

<sup>27</sup> Phosphoric acid solidifies at 42 ± 5°C.

*Molten carbonate fuel cells:* in this type of cell the electrolyte is made up of a mix of alkaline carbonates (lithium, potassium, sodium) in a lithium—aluminium porous matrix. Electrodes are in a nickel alloy with 10% of chromium (anode) and porous nickel oxide with 1–2% of lithium (cathode).

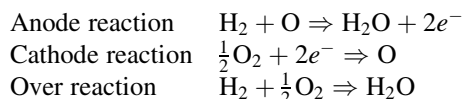
The reactions in a MCFC are the following:



These cells need to be fed at the cathode, besides with oxygen (or air), also with carbon dioxide.<sup>28</sup> This makes them particularly suitable to be fed with hydrogen locally produced by gas reforming: in this case it is possible to use the CO<sub>2</sub> produced by the reforming system for the cathode supply of the cell. Thanks to the high operating temperatures (to keep molten salts the operating temperature of the cell must exceed 600°C), internal reforming is possible; by powering the cell with CH<sub>4</sub> and H<sub>2</sub>O (steam), the reforming reactions take place first, followed by the already seen anodic reactions. Furthermore, high temperatures allow these cells to present a high tolerability to impurities.

*Solid Oxide Fuel Cells:* in this type of cell the electrolyte is made up of ceramic material (yttrium-zirconium oxide) with a thickness of 30–40 µm. Electrodes are free from platinum; the anode is of cobalt or nickel zirconium oxide and the cathode of strontium-doped lanthanum magnetite.

The H<sub>2</sub> reactions in a SOFC are the following:



The co reactions in a SOFC are the following:

In these cells, the presence of gas and solid phases alone reduces the corrosion problems, whereas high temperature reduces the polarisation losses and markedly improves the tolerance to impurities. For SCFC, CO is not a poisoning agent but rather a fuel (namely it actively participates in electrochemical reactions); CH<sub>4</sub> can be inert (while not participating in reactions, it does not cause any damages) or fuel; H<sub>2</sub>O and CO<sub>2</sub> are inert, whereas the compounds of Sulphur are harmful in concentrations exceeding 1 ppm.

<sup>28</sup> The quantities of CO<sub>2</sub> requested are by far higher than those normally contained in the air: two moles of CO<sub>2</sub> every mole of O<sub>2</sub>. Air contains nearly 20% (in moles) of oxygen and 388 ppm (parts per million) of CO<sub>2</sub>, which accounts for 0.039%. Therefore, on average, in the air the ratio CO<sub>2</sub>/O<sub>2</sub> amounts to 0.00195, that is to say over 1,000 lower than the one demanded.

*Fields of Application, Costs and Perspectives of Fuel Cells*

After space applications, recently, fuel cells were extensively used in the field of electric power production, both in large power plants and for the small scale production “on site”. Power plants were installed in several places, in Japan, in Europe and in the USA, where a passage occurred from the prototype phase to the technical–economic evaluation phase.

In the military field, fuel cells are used in submarines and in ground vehicles, thanks to their low noise level and thermal “trace” that makes their infrared detection difficult, whereas there are minimum applications under study in the surface naval sector.

In general, the most interesting applications, to the purpose of a large-scale development of the technology of fuel cells, include the electric power generation for stationary use (in cogeneration), the sector of vehicles and that of portable electronics.

**Stationary Use:** For the production of electric power, fuel cells show several advantages compared to conventional systems, including:

- Higher flexibility of use since they are more suitable to meet the needs of a variable load, whereas their efficiency is not linked to the size of the plant
- Higher electric efficiency
- Lower environmental impact
- Higher easiness of planning and construction: thanks to their modular structure, the construction times can be strongly reduced and the power of the plant can be increased over time.

Cogeneration (and distributed generation in general) meet environmental (low emissions) and socio-political (management and control at a local level, competitiveness and quality and flexibility of services) needs, that will become increasingly important in the medium-long term. It is therefore possible to envisage a growing space for small-medium size generation technologies, with a high efficiency and a limited environmental impact, as fuel cells. It is predictable in the short-medium term that the various types of cells, according to their different operational characteristics (operating temperature, efficiency, size, etc.), can be used for distributed generation and cogeneration for civil and industrial use, for powers ranging between some kW to some MW.

**Transports:** in the sector of transports, fuel cells show advantages compared to both internal combustion engines (ICE) and an electric powertrain vehicle with accumulators. The use of hydrogen-supplied fuel cells allows to have zero emission vehicles (ZEV) eliminating in this way the pollution problems linked to the use of ICE without the limits of electric powertrain vehicles with accumulators (high weight, low autonomy, long recharge times). As concerns electric vehicles, it is important to underline that both fuel-cell powered vehicles and vehicles powered through accumulators are driven by an electric motor: the two solutions, therefore, shall not be necessarily considered as alternative to one another. On the contrary, the experiences developed in the last few years show that the adoption of “hybrid”



solutions (fuel cells for the production of electric power onboard together with both traditional storage systems—accumulators—and new generation ones—supercapacitors) allow to conjugate the high efficiency of electric vehicles with accumulators without the limits due to the limited range and the long recharge times.

Among all the types of cells, the polymer electrolyte membrane (PEM) fuel cells are those that, in consideration of their working temperature, power, weight and size, are suitable for the applications in the sector of transports.

**Portable applications:** in the field of portable electronic equipments, batteries are at the moment the only possible option for products that require a power up to 100 W. The limits of batteries in the applications, for instance, for notebooks, are determined by weights and sizes, by the limited autonomy, the recharge times and their replacement which entails disposal problems. A fuel cell might, conversely, supply energy for times very much higher than present Li-ion batteries. Furthermore, given the same weight, hydrogen-rich fuels contain electrochemical energy that is two order of magnitude higher than whatever type of battery. These considerations led to the development of testing activities for the use of fuel cells for small electronic units that need high-quality power supply.

The main problems to be solved are linked to the complexity of the internal design of the device, in particular as concerns the storage hydrogen subsystems, fuel and oxidant control, and cooling system. Miniaturisation entails therefore a delicate balance of different factors, such as power, size, handiness and costs.

### *Costs and Perspectives*

The present development led to obtain high specific powers; for instance PEMs, that, as already said, are particularly suitable for the drive, have a specific power of about 1 kW/l (corresponding to a volume of nearly 50 litres for a medium-power vehicle). Another crucial factor for the development of fuel cells is duration; presently, in case of low-temperature cells, this duration is around 3,000–3,500 h, whereas it reaches nearly 5,000 h in case of high-temperature cells. Costs vary according to the type of cells and their size.

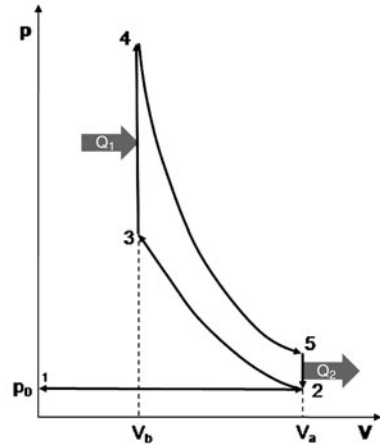
The following targets in terms of costs and duration were set as far as marketing is concerned: 100 €/kW and 5,000 h of operation for low temperature cells for the powertrain. This duration corresponds, in case the system is assembled on a car, to about 100,000 km of mileage. In case of stationary plants, objectives include a cost not exceeding 1,000 €/kW and a duration exceeding 40,000 h.

## ***4.2.4 Chemical Energy-to-Mechanical Energy Conversion Plants***

### **4.2.4.1 Internal Combustion Engines**

In these systems, the chemical energy of a fuel is converted into heat through combustion; such heat is converted into mechanic energy through a

**Fig. 4.34** Ideal Otto cycle on plane  $p$ – $V$



thermodynamic cycle. The most widespread application is in the sector of transports; in this case the “useful” energy is the mechanic one. In any case, mechanical energy (on a rotating shaft) can be easily converted into electric energy through a generator coupled to the shaft (ICE power-supply units): in this case the system as a whole performs a conversion from chemical energy to electric power.

ICE can be classified according to the thermodynamic cycle: the main ones are the Otto cycle and the Diesel cycle.

### *Otto Cycle*

Figure 4.34 shows the ideal Otto cycle  $p$ – $V$ . The engines adopting this cycle can be fuelled with petrol, LPG, hydrogen and methane, or a mix of them.

The following phases can be identified in the Otto cycle:

- 1–2: Constant pressure aspiration of the air–petrol mixture;
- 2–3: Rapid compression, ideally an adiabatic one, of the mixture;
- 3–4: Combustion, phenomenon summarised through an isochoric heating;
- 4–5: Rapid expansion, ideally an adiabatic one;
- 5–2: Opening of the discharge valve with isochoric reduction of pressure;
- 2–1: Exhaust at constant pressure.

The ideal efficiency of a thermodynamic cycle is:

$$\eta_{id} = \frac{L}{Q_1} \quad (4.87)$$

For the Otto cycle there is:

$$L = Q_1 - Q_2 = c_v(T_4 - T_3) - c_v(T_5 - T_2) \quad (4.88)$$

By combining the better two equations and assuming  $c_v$  as constant one carry to:

$$\eta_{id} = 1 - \frac{T_5 - T_2}{T_4 - T_3} \quad (4.89)$$

Applying the equations of the related thermodynamic transformations (adiabatic and isobaric) of the cycle, then

$$\frac{T_3}{T_4} = \frac{T_2}{T_5} \quad (4.90)$$

one comes to:

$$\frac{T_5}{T_4} = \left( \frac{V_b}{V_a} \right)^{\gamma-1} \quad (4.91)$$

Considering (4.90) and (4.91), (4.89) can be written as follows:

$$\eta_{id} = 1 - \frac{T_5}{T_4} \cdot \left( \frac{1 - T_2/T_5}{1 - T_3/T_4} \right) = 1 - \frac{T_5}{T_4} = 1 - \left( \frac{V_b}{V_a} \right)^{\gamma-1} \quad (4.92)$$

Having defined the compression ratio  $r$  as follows:

$$r = \frac{V_a}{V_b} \quad (4.93)$$

the ideal efficiency of the Otto cycle is:

$$\eta_{id} = 1 - \frac{1}{r^{\gamma-1}} \quad (4.94)$$

It is evident how the ideal efficiency increases as the compression ratio increases; in the practical Otto cycles, however, it is not possible to exceed a compression ratio of 8–10 in order to avoid the self-ignition of the mixture that would occur during the compression phase, before the piston reaches the top dead centre, since a fuel–air mix is compressed and in some temperature and pressure conditions, it spontaneously burns out.

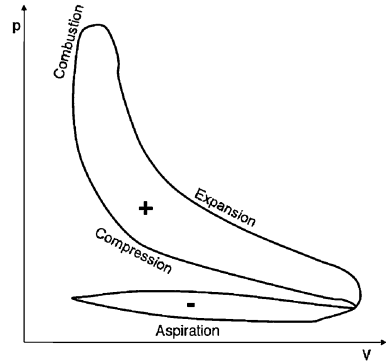
With  $\gamma = 1,4$  and  $r = 8$ , the ideal efficiency is 56.5%. The real cycle (Fig. 4.35) is very much different from the ideal one, having considered the irreversibility of transformations and most of all the fact that induction and exhaustion do not take place at constant pressure, generating in this way a negative work in the cycle.

The maximum efficiency<sup>29</sup> of the real cycle amounts to about 25%. If the engine operates at a variable speed (automotive powertrain), considering the operation at variable speed the average efficiency drops at nearly 18–20%.

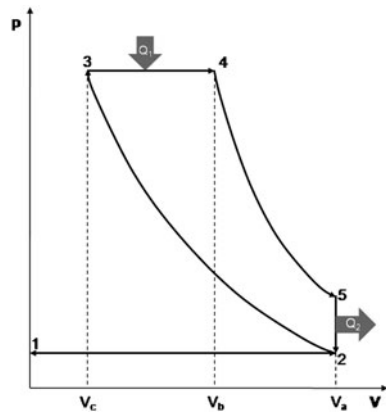
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<sup>29</sup> The efficiency of the real cycle (differently from the ideal one) varies according to the number of revolutions of the engine and presents a maximum of nearly 2/3 of the maximum number of revolutions.

**Fig. 4.35** Real Otto cycle on plane  $p$ - $V$



**Fig. 4.36** Ideal Diesel con plane  $p$ - $V$



### *Diesel Cycle*

Figure 4.36 shows the Diesel cycle  $p$ - $V$  diagram. Engines adopting this cycle can be fuelled with gas oil.

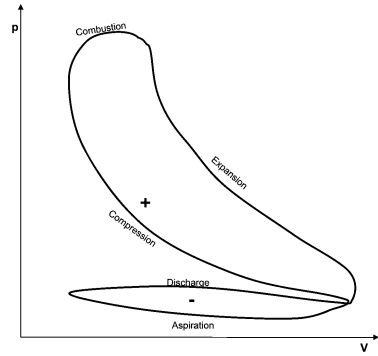
In the Diesel cycle the following phases can be identified:

- 1–2: Aspiration at constant pressure of air only;
- 2–3: Rapid compression, ideally an adiabatic one;
- 3–4: Combustion, which takes place by introducing the fuel when air has reached the conditions suitable for air–fuel mixture burns spontaneously, a phenomenon that can be regarded as isobaric heating;
- 4–5: Rapid expansion similar to an adiabatic;
- 5–2: Opening of the discharge valve with isochoric reduction of pressure;
- 2–1: Exhaust at constant pressure.

For the Diesel cycle there is:

$$L = Q_1 - Q_2 = c_p(T_4 - T_3) - c_v(T_5 - T_2) \quad (4.95)$$

**Fig. 4.37** Real Diesel cycle on plane  $p$ - $V$



Therefore, considering  $c_p$  and  $c_v$  as constants, the ideal efficiency is:

$$\eta_{id} = \frac{L}{Q_1} = 1 - \frac{c_v T_5 - T_2}{c_p T_4 - T_3} = 1 - \frac{1}{k} \frac{T_5 - T_2}{T_4 - T_3} \quad (4.96)$$

Applying the equations of thermodynamic transformations (adiabatic and isobaric) of the cycle, then:

$$\frac{T_4}{V_c} = \frac{T_3}{V_b} \quad (4.97)$$

Considering (4.96), (4.97) becomes:

$$\eta_{id} = 1 - \frac{1}{\gamma} \cdot \frac{1}{(V_a/V_b)^{\gamma-1}} \left( \frac{(V_c/V_b)^{\gamma} - 1}{(V_c/V_b) - 1} \right) \quad (4.98)$$

Defining the following ratios:

$$r = \frac{V_a}{V_b} \quad (4.99)$$

$$e = \frac{V_a}{V_c} \quad (4.100)$$

Replacing (4.99) and (4.100) in (4.98), the efficiency can be written as follows:

$$\eta_{id} = 1 - \frac{1}{\gamma} \cdot \frac{(1/e)^{\gamma} - (1/r)^{\gamma}}{(1/e) - (1/r)} \quad (4.101)$$

In this case as well, efficiency increases as  $r$  increases. In the case of the Diesel cycle, however, the real value of  $r$  can be higher than in the case of the Otto cycle since, by compressing only air, the problem of self-ignition does not appear; the effective values of  $r$  can be 18–20. With  $r = 18$  ( $e = 9$ ) a value of the ideal efficiency is obtained as amounting to 63.2%. Also in this case as well, the real cycle (Fig. 4.37) is heavily different from the ideal one for the reasons seen above. The maximum

efficiency values of the real cycle are around 35% and, during operation at variable speed, the average value of efficiency drops at around 25–28%.

### 4.2.5 Radiant Energy-to-Thermal Energy Conversion Plants

Solar energy can be captured and used in a thermal form, and this can happen *without concentration* (thermal solar at low temperature) or *with concentration*.

In the case of concentration plants, there are two different applications:

1. The systems with a limited concentration, in which case the thermal energy will have a relatively low operational temperature (i.e. up to 250° C) and heat is used for process purposes, whenever a thermal source is needed, i.e. for drying purposes in agriculture or for chemical-industrial processes.
2. The systems with a high concentration, in which case maximum operational temperature is high and applications can include industrial processes or thermodynamic conversion to produce electric power.

#### 4.2.5.1 Low-Temperature Thermal Solar Plants

The main application of this conversion technology is that of capturing solar radiation energy and, by means of it, to heat water (at 40–70°C) for sanitary use destined to civil and residential applications.

There are several types of plants and can be used for different purposes according to the performance of the collector, the place in which they are located and the types of users they have to serve.

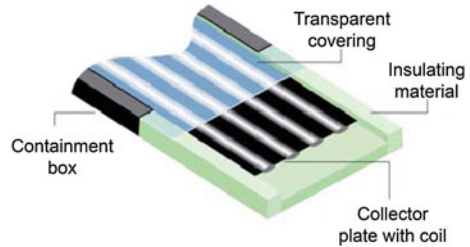
A basic solar thermal system is made up of four main elements that are listed below:

- Solar panel (collector)
- Storage reservoir
- Control unit
- System of pipes and circulation pump.

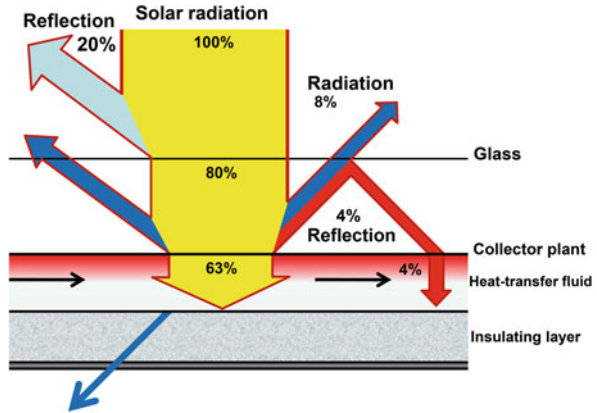
#### Flat-Plate Solar Collectors

A flat-plate solar collector (Fig. 4.38) is made up of a *transparent covering* with one or several glass or plastic sheets placed at the top of the absorbing plate to reduce convective and radiation thermal exchanges between the plate and the atmosphere, and a *black absorbing plate* that absorbs the radiation and transfers the energy collected to a heat-transfer fluid, one layer of *thermal insulation* to reduce as much as possible the losses due to plate conduction, and of one

**Fig. 4.38** Elements making up a solar collector



**Fig. 4.39** Thermal flows in a solar collector



parallelepiped-shaped *covering* with a task of containment and protection from dust, humidity, etc.

Figure 4.39 shows the energy flows of a typical flat-plate solar collector. A part of the incident solar energy on the glass coating is reflected, a fraction is absorbed by the glass itself, another reaches the capturing plate. A part of such energy is reflected, another part is absorbed by the plate. Some amount of the energy reflected by the plate is in turn reflected by the glass coating, hence going back again to the capturing plate, and the phenomenon is repeated originating a greenhouse effect inside of the collector.

On the basis of the description above, it is evident that in order to have a suitable capturing of the incident energy, the covering sheet must be extremely transparent ( $\tau \cong 1$ ) at wavelengths in which there is the maximum possible solar radiation (between 0.4 and 2.5  $\mu\text{m}$ ). After being reached by the solar radiation, the absorbing plate absorbs most of it, subsequently emitting energy in the form of thermal radiation, whose wavelength,  $\lambda$ , (in  $\mu\text{m}$ ) depends on the level of temperature  $T$  (K) according to Wien's law:

$$\lambda = \frac{2897.8}{T} \quad (4.102)$$

Since the operating temperature of the collector plate is usually around  $100^\circ\text{C}$  (373 K), the energy released by the plate falls within the field of wavelengths

corresponding to the infrared (nearly  $7.7 \mu\text{m}$ ). Therefore, to maximise the useful energy, the transparent covering should reflect ( $\rho \cong 1$ ) these wavelengths. Obviously, the collecting plate must be as absorbent as possible ( $\alpha \cong 1$ ) for all the wavelengths, and have a low submissiveness for the wavelengths of the infrared.

The collecting plate, made in copper or steel, is superficially treated with dark and opaque paints that reduce reflection and increase absorption (low emissivity for wavelengths, typical of infrared radiation). The main function of the plate is to divert heat and send it to the pipes: it is important to privilege those solutions in which the thermal resistance between said elements is reduced to minimum levels (for instance welded pipes and plate). Normally, canalisations are made to resist pressures of 6–7 bar.

The insulating material, with a porous structure, has to reduce at minimum the losses due to conduction towards the lateral and lower surfaces of the collector. The materials that are mostly used include polyurethane, polyester wool, glass wool or rock wool (sheets, rolls, pressure-injected foams). Thermal insulation gives out in case of storage of humidity (often, therefore, a sheet of aluminium is placed on the insulating plates with the aim of stopping condensation and reflecting the radiation coming from the plate towards the plate itself).

The transparent covering, as already mentioned, must be extremely transparent for the wavelengths typical of solar radiation and, at the same time, opaque to infrared radiation. The materials most frequently used for its implementation include: *single glass* (very good transparency without blocking convection losses, it is heavy and fragile), *double glass* (decreases transparency but increases the thermal insulation capacity), honeycomb polycarbonate (light, inexpensive, resistant, it is characterised by reduced convection losses compared to the single glass, although it is less transparent, tends to be opaque in time and, therefore, its lifecycle is shorter than the collector).

The containment case gives compactness and mechanical strength to the collector, and aims at protecting the internal elements from dirt and atmospheric agents. The materials that are usually used to realise it include stainless steel (generally galvanised and pre-treated), anodised aluminium or, more rarely, fibreglass.

The heat-transfer fluid must have a limited volume (in order to use small-size pipes), a high density and a high specific heat. It shall not be corrosive for the circuit, and must be chemically inert and stable at temperatures around  $100^\circ\text{C}$ . It is also necessary that the fluid selected has a low hardness in order to limit the limestone deposition, besides having a low freezing point and a low viscosity (in order to favour an easy flowing of the fluid without introducing excessive load losses in the circuit). In those cases in which the collector is used to supply sanitary hot water, it shall not be toxic (otherwise there would be huge complications of the system for safety reasons). Fluids that corresponding to these characteristics, at limited costs, include *water* (characterised, however, by non negligible problems of hardness and also an easily reachable freezing point in areas with a temperate climate), *a solution of water and ethylene glycol* (toxic and not suitable to systems for the production of sanitary hot water (SHW)) or, in most of cases, *a solution of water and propylene glycol*.



Indicating with  $Q$  the incident flow, with  $Q_u$  the flow of useful heat, with  $Q_p$  the flow of dissipated heat, the balance can be written as follows:

$$Q = Q_u + Q_p \quad (4.103)$$

Indicating with  $\tau$  the transmittance of the transparent coating, with  $\alpha$  the absorbance of the collecting plate, with  $I$  the incident solar radiation and with  $A$  the active surface of the collector, the total incident flow is:

$$Q = I \cdot \tau \cdot \alpha \cdot A \quad (4.104)$$

With reference to *specialised* literature, the flow of dispersed heat (sum of thermal losses and of optical losses) can be expressed as:

$$Q_p = U_c(T_p - T_a) \quad (4.105)$$

where  $T_a$  is the ambient temperature,  $T_p$  is the collecting plate average temperature,  $U_c$  is the *thermal dispersion coefficient of the collector* that depends on the convective and radiation thermal exchange coefficients with the environment and can be considered as constant within a limited range of temperatures.

From (4.103), (4.104) and (4.105), it is possible to obtain:

$$Q_u = (\tau\alpha)I - U_c(T_p - T_a) \quad (4.106)$$

In (4.106), however, the useful energy is expressed according to the average temperature of the plate, which is unknown. From an operational viewpoint, it is possible to use to this end the Bliss equation that expresses the useful energy according to the temperature of the fluid at the entry point of the collector  $T_i$ :

$$Q_u = F_r[(\tau\alpha)I - U_c(T_i - T_a)] \quad (4.107)$$

$F_r$  is the *factor of thermal removal of the collector*, always lower than 1. It physically represents the *ratio between the useful energy actually collected and the energy that would be collected if the entire plate had been at the same temperature as the outlet fluid*. This condition might only be assessed in ideal conditions: infinite fluid flow rate and null thermal resistance between fluid and plate.  $F_r$  mainly depends on the convection coefficient for fluid and plate, on the thermal conductivity between plate and the canalisation.

Some reference values of the parameters used in the Bliss equation are shown in Table 4.6.

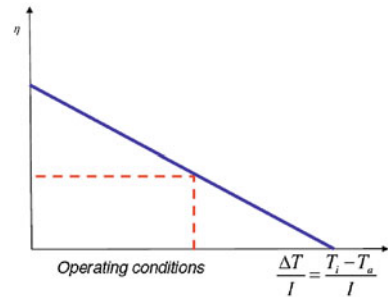
The *efficiency of a solar collector* is defined as the ratio between the useful energy collected in a given period of time and the incident solar energy in the same period:

$$\eta = \frac{Q_u}{I} \quad (4.108)$$

Replacing (4.107) in (4.108), it follows that:

**Table 4.6** Values of the parameters for the calculation of useful energy

Parameters for the calculation of useful energy		
Thermal loss coefficient $U_c$ (W/m <sup>2</sup> K)	Non-selective plate and simple glass transparent covering	7–8
	Non-selective plate and double glass covering	4–6
	Selective plate and double transparent covering	3–5
Effective product $\tau\alpha$	Simple glass covering	0.9
	Double glass covering	0.8
Thermal removal factor $F_r$	Liquid collectors	0.9
	Air collectors	0.7

**Fig. 4.40** Efficiency of a solar collector as operating conditions vary

$$\eta = F_r(\tau\alpha) - \frac{F_r U_c (T_i - T_a)}{I} \quad (4.109)$$

Since  $F_r(\tau\alpha)$  and  $F_r U_c$  can be considered as constant, the efficiency depending on the variable  $T_i - T_a / I$  is an angular coefficient line  $F_r U_c$ , as shown in Fig. 4.40.

The results obtained are supported by the experimental analysis, from which it emerges that efficiency has an almost linear trend, sloping down as temperature increases due to the variation of  $U_c$ . As wind speed increases, efficiency is reduced by some percentage points with more marked variations over the speed of 5 m/s, and as the temperature of collectors increases. The influence of wind is negligible for those collectors endowed with two or more transparent coverings.

The intersection of the efficiency line with the axis of abscissas defines the *stagnation temperature* that, after setting room temperature and the intensity of the incident radiation, represents the temperature at which the plate is taken in conditions of null useful energy.

#### *Performance of flat-plate collectors influence parameters*

At the usual operating temperatures (40–60°C) for a non-selective flat-plate collector and a glass covering, thermal dispersions are due to 10% only to posterior and lateral conduction losses. The remaining part is equally divided into losses due to convection and radiation between plate and glass. For this reason, it is not possible to obtain remarkable advantages by increasing the thickness of posterior

insulation beyond the 5–10 cm that are usually used, whereas there are considerable reductions of losses by taking care of the elimination of all possible thermal bridges, the most common of which is represented by the plate-external covering contact outside of the collector.

Particular importance is also ascribed to the characteristics of the insulating material that shall not degrade over time because of severe thermal stresses. Since the radiation exchange depends on the fourth magnitude of absolute temperature, as temperature increases, radiation dispersions increase as well, which explains the use of selective plates when operating temperatures are higher. This intervention, however, in lowering the equilibrium temperature of glass, stresses the convective losses between plate and glass; this increase, however, is lower than the reduction of dispersions by radiation.

Dispersions by convection can be drastically reduced, creating vacuum between the plate and the glass, with pressures lower than 10 mbar as it happens in vacuum collectors.

To increase  $F_r$ , it is possible to increase the flow rate which should be included between the minimum value of  $0.007 \text{ kg/m}^2\cdot\text{s}$ , necessary to guarantee a sufficient irrigation of all canals, and the maximum value of  $0.03 \text{ kg/m}^2\cdot\text{s}$  beside which the advantages of the best thermal exchange can be overcome by an increased pumping activity. As the flow rate decreases, the temperature drop between the input and the output of the collector increases, and therefore also the instantaneous efficiency, which in the long term may cause a penalisation of the overall performance, is reduced. The  $F_r$  increase is also obtained by paying attention to the thermal exchange between plate and canalisation, which might also be limited in the case of canalisations welded to the plate. Furthermore, it is important that the plate has a good thermal conductivity, which might be obtained by using metals as copper (which shows the best conductivity), aluminium and steel.

Apparently, performance should be penalised as the thermal capacity of the collector increases, because of the impossibility of exploiting short favourable periods, characteristic of a variable climate.

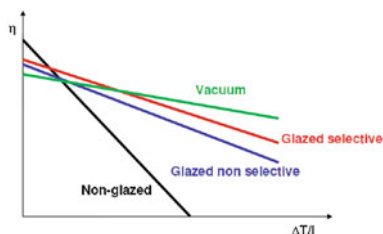
#### *Types of flat-plate solar collectors*

Besides the glazed ones mentioned above, there are other types of collectors: *uncovered*, *integrated-storage* and *vacuum*.

Uncovered collectors, made with plastic pipes (propylene, neoprene, synthetic rubbers, PVC) have the advantage of being cost-effective in some conditions although free from any type of insulation and transparent cover, and provide satisfactory performance only if used for plants working in the summer period, when the great availability from the solar source makes up for their low efficiency.

In integrated storage collectors, a single element replaces the collecting plate, the coil and the external storage; this single element can be made up of siding pipes (diameter of nearly 10 cm), large pipes between two plates facing each other, and a single large container of different shapes. The water necessary for users remains inside of the collector (slow heating with convective motions).

**Fig. 4.41** Efficiency curve of the different types of flat collectors



In order to have an idea on the difference compared to flat collectors, it is enough considering that the water content reaches 80–100 l/m<sup>2</sup> against 0.6–2 l/m<sup>2</sup> of heat-transfer fluid, typical of the devices with external storage. Since water remains is a “reservoir” insulated only along three sides out of four, this type of collector is characterised by non-negligible leakages and is suitable for particularly mild climates.

Vacuum collectors are those with the highest efficiency; by reducing at minimum levels the presence of air in hollow spaces, it is possible, as a matter of fact, to avoid the losses due to convective motions. Although more expensive compared to the average, these collectors allow good performance also with harsh climates.

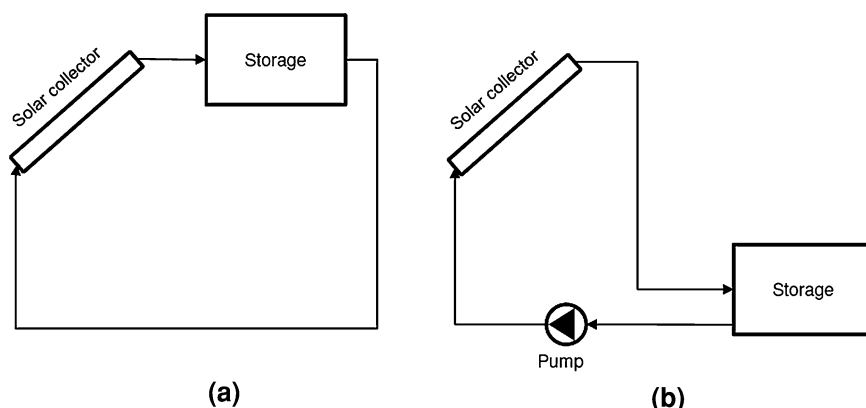
From Fig. 4.41, showing the comparison between the efficiency curve of the different types of flat collectors, it is possible to note that the efficiencies of the different types of solar collectors are basically the same for low values of the difference between the temperature of the collector and the ambient temperature. In fact, the different solutions adopted (the covering, eventually selective, the vacuum inside of the collector) aim at reducing leakages. These leakages, for obvious reasons, are in any case limited for the low values of difference between the temperature of the collector and the ambient temperature; as it increases, the leakages for the different types markedly increase. In particular, vacuum collectors keep high efficiencies also at high temperatures.

### *Plant solutions*

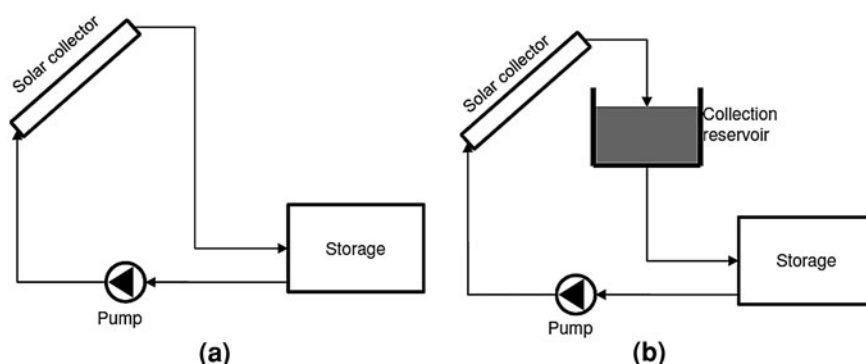
As concerns the configuration of the plant, *natural circulation* and *forced-circulation plants* are to be considered.

In natural circulation plants, the force of the heat-transfer fluid occurs on the basis of a different density between the hottest water column flowing out of the collector, which tends to increase, and the coldest water column flowing out of the storage reservoir, which tends to increase (Fig. 4.42a). The higher the difference in temperature between the two columns of fluid, the higher the force that allows its circulation. In natural circulation systems, panels must be positioned lower than the storage area. The difference between the two levels as well is proportional to the force generated.

In forced-circulation plants, the fluid is set in motion by a centrifugal pump (Fig. 4.42b); in that case, obviously, position different in the storage can occur.



**Fig. 4.42** Natural (a) and forced (b) circulation plant configurations



**Fig. 4.43** Plant configuration: closed systems (a) and draining systems (b)

Another distinction in the plant configuration concerns the state of the circuit when the plant is stopped: there are *closed-loop systems* and *drainback systems* (Fig. 4.43).

In closed-loop systems, solar collectors are always loaded with fluid, even when the circulation pump is stopped. In this case the heat-transfer fluid must be able to face low temperatures without freezing, and impose the use of an antifreeze liquid: this prevents the direct exchange. In closed systems it is always necessary to interpose a heat exchanger between the solar circuit and the users.

In drainback systems, as soon as the circulation pump stops, the solar circuit empties in a drainage reservoir, placed under collectors themselves. Since one better avoid using antifreeze liquids, open systems can be used with a direct exchange without placing any exchanger between the plant and users that, obviously, entails a higher complication of the system and an overall loss of efficiency. Conversely, the disadvantage of direct exchange systems that use running water as heat-transfer fluid is the danger of calcareous deposits on the internal walls of pipes.

Another variant of low-temperature solar plants concerns the *storage system*, which is generally provided: plants may have either an *integrated storage reservoir* or an *external storage reservoir*.

In integrated storage reservoirs, each panel has its own “integrated” reservoir. As a matter of fact, generally, the system is more compact, installation is easier and it is possible to eliminate the external reservoir that is unaesthetic and bulky. It is also possible to eliminate the hydraulic circuit between collector and storage and the storage heat exchanger which always implies a loss of efficiency.

In the systems with external storage reservoirs, which are necessary when users have a remarkable thermal load, the heat transfer between the solar collector circuit and the users’ circuit occurs in the storage phase.

Two types of heat exchangers can be used: *tube-bundle* and *cavity* ones.

In tube-bundle exchangers, a series of tubes is inserted in the low part of the storage. Sometimes, two groups are inserted with a view to heating the fluid contained in the storage with two different sources of heat (solar system and integration boiler).

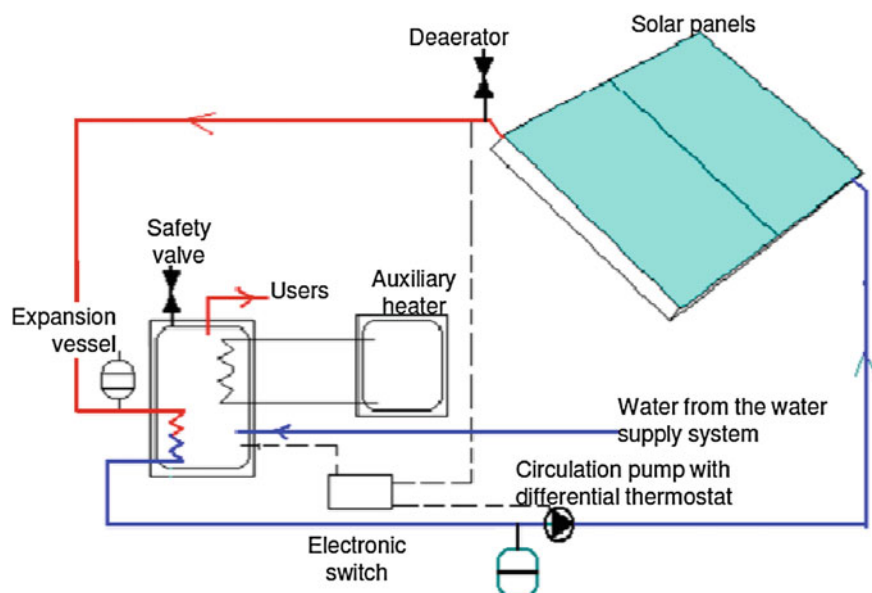
In order to avoid the formation of electric current, given the presence of different metals in a saline solution (water always contains dissolved salts) *an anode is inserted* (negative metal compared to the others), which eliminates this problem. The anode is inserted in an orifice place at the bottom of the reservoir. From the same point, probes, thermometers and all the control equipment are inserted.

A cavity exchanger consists in a hollow space obtained in the cylindrical wall of storage. The fluid coming from solar collectors exchanges counter-current its thermal energy with the fluid contained in the storage. Sometimes two cavities are obtained in the wall to allow the thermal exchange from two different sources of heat.

### *Heat storage*

Since solar radiation and consumption of thermal energy do not happen simultaneously, it is necessary to include a heat storage reservoir in the plant. Heat storage can be done on a daily, weekly or seasonal basis. For the sizing of storage (usually daily) it is necessary to refer to the diagrams of daily heat production and needs.

In any case, seasonal storage is also possible. There are two storage systems: the first one (very much used in northern European villages), is obtained by *digging in rocky masses* a cave with a capacity between 100 and 1000 m<sup>3</sup>. If there are no aquifers nearby, the rock, once filled with hot water, reaches a stable thermal equilibrium. The reservoir is sized to meet the thermal needs from September to the end of February. In March the direct use of water from solar collector begins once again. Very often the heat coming from inter-season storage is integrated with chimney boilers. In the second one (very much used in Middle East) systems called “*Solar Pond*” are made. These are large artificial reservoirs; the bottom of the reservoir is made in black plastic or in any other material provided that it is safe (sometimes also seaweeds). The reservoir is divided into two layers through a polyethylene film or in any case with a transparent plastic: the most



**Fig. 4.44** Diagram of a forced-circulation and closed-circuit integrated system

superficial layer is filled with freshwater, the deepest layer with saltwater. The transparent film acts as a selective material. The temperature of deep saltwater reaches even  $90^{\circ}\text{C}$ .

The weekly storage aims at ensuring the availability of heat in long periods with a low or very low solar radiation. In this case the storage system is a reservoir of such size that guarantees a reserve of thermal energy. Storage can be done through a single reservoir or with several reservoirs, one of which has to be sized for the daily needs of the normal period of use, whereas the secondary ones must be used according to the quantity of storage thermal energy selected. In case of the Mild climate areas, weekly coverage solutions are avoided, since they are more suitable for cold climate regions.

### *Integrated plants*

Given the uncertainty of the source, solar collector plants, in order to guarantee the continuous availability of heat to users, must usually be integrated with traditional plants. The heat produced from solar energy will integrate the one produced in traditional boilers: the integration factor is determined according to technical-economic considerations, normally around at least 60%.

The insertion is extremely simple in case of integrated storage in the collector. In fact, having considered that the hydraulic circuit between collectors and storage is not present, any control equipment is necessary (*differential thermostat* and *minimum thermostat*). The solar collector can be installed upstream the integration

boiler and uses the thermostat of the integration system (gas boiler or electric water heater) as a control of the system. Modern gas boilers and electric water heaters can be crossed by hot water. The load losses of the fluid in crossing the boiler are limited, having considered that the length of the coils inside of it does not exceed two meters in linear length. A scheme of integrated plants is shown in Fig. 4.44.

#### 4.2.5.2 Solar Thermal Concentration Plants

Flat-plate solar collectors work with acceptable efficiencies at low temperatures. To obtain heat at higher temperatures, the so-called *concentration plants* are used.

Concentration solar collectors use optical systems aimed at increasing the intensity of radiation on the collecting surface.

Figure 4.45 shows a scheme of the operating principle: in principle, the incident radiation of a suitable sized and shaped concentrator is reflected and concentrated in one point (as a matter of fact, on a surface small if compared to the one of the concentrator), the receiver. It is evident from the figure that these systems, since they operate according to the optical reflection principle, exploit only the direct component of solar radiation, since the diffuse radiation reaches the receiver while being distributed in all directions. Furthermore, for the same reason, they must be endowed with a tracking system, since the angle of incidence of the radiation compared to the normal tangent of the concentrator in a point must remain constant.

When the solar radiation incident on a given surface is concentrated on a smaller one, thermal losses, being them proportional to the exchange surface of the absorbing body, are lower. The ratio between the area of the reflecting surface  $A_r$  and the absorbing surface  $A_a$  is called *concentration factor*. This value, for the different concentration systems, varies from 1.5 to 10,000; as the concentration factor increases, optical losses become increasingly relevant.

As shown in Fig. 4.46 there are three types of concentrators which are used in concentration solar thermal plants: *linear parabolic concentrators*, *parabolic dish concentrators*, and *central receiver concentrators*.

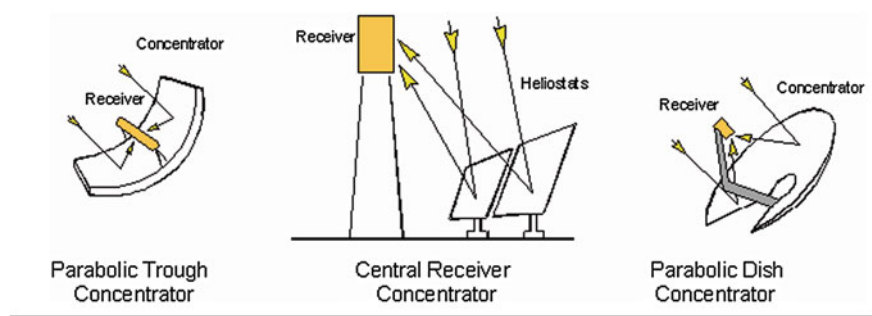
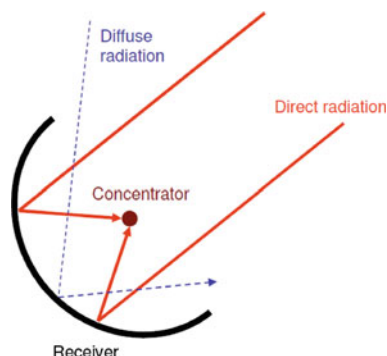
In *linear parabolic concentrators*, the radiation is concentrated along a line that covers the entire length of collectors; along such a line there is a pipe containing the heat-transfer fluid. Collectors follow the sun by rotating around an axis. With these systems, temperatures of around 400°C are reached, with good efficiencies.

In *parabolic dish concentrators*, the solar radiation is concentrated in a point in which there is a device that absorbs the radiation and transfers heat to a gas. The concentrator “follows” the sun rotating around two axes. With these systems, temperatures of around 750°C can be reached.

*Central receiver parabolic concentrators* are made up of a large field of heliostats and a receiver placed on a tower. A heliostat is a flat mirror that moves (to follow the sun) independently from the others by rotating around two axes. With these systems, it is possible to reach temperatures around 1,000°C.



**Fig. 4.45** Scheme of the operation principle of a concentration system



**Fig. 4.46** Different types of concentrators

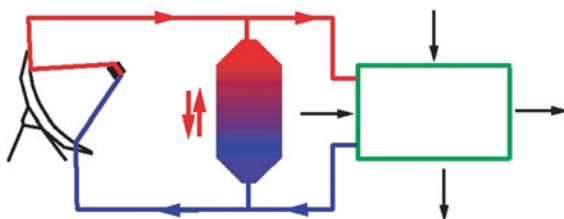
The heat produced by concentration solar plants has different types of applications. It can be used by the industrial sector as process heat, or to feed a thermoelectric (steam) plant; in this case, the plant as a whole operates a conversion from radiant energy to electric energy. Another possible application (for those operating at high temperatures, that is to say dish concentrators and solar-power towers) consists in providing the necessary heat for the thermodynamic fission of water to produce hydrogen. In that case, the plant as a whole performs a *conversion from radiant energy to chemical energy*.

## 4.2.6 Thermal Energy-to-Chemical Energy Conversion Plants

### 4.2.6.1 Thermolysis

In general, the thermolysis process consists in the fission of the water molecule into hydrogen and oxygen, using heat for the fission reaction  $\text{H}_2\text{O} + \text{heat} \Rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2$ . Thus it is a system converting thermal energy to chemical energy. Heat can be produced in different ways, and several studies

**Fig. 4.47** Diagram of a solar thermolysis plant [3]

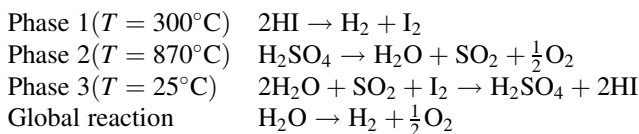


assess such technologies. One option is to exploit the heat produced in thermoelectric plants: the thermolysis allow a *transformation of chemical energy* (a fossil fuel is used as a primary resource, and another fuel is produced, hydrogen). Also heat produced in nuclear plants can be used: in this we have a *conversion from nuclear power to chemical energy*. Another possibility consists in the use of concentrated solar energy, which allows to reach very high temperatures; in this case the plant operates a *conversion from radiant energy to chemical energy*.

In any case, the reaction of direct fission of water, heavily endothermic, without the use of catalysts, takes place at very high temperatures (besides 2,000°C). To obtain the fission at lower temperatures, it is necessary to use particular catalysts forming intermediate compounds.

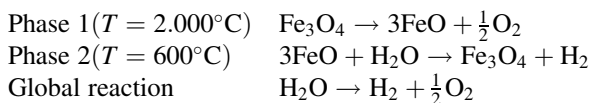
When heat is produced by thermoelectric or nuclear power plants, a promising chemical process is the one made up of three phases: *thermal decomposition of hydrogen iodide* from which  $H_2$  and  $I_2$  are obtained; *thermal decomposition of sulphuric acid*, from which  $SO_2$  and  $O_2$  are obtained; *reaction of  $I_2$  and  $SO_2$* , in aqueous solution at ambient temperature, from which  $HI$  and  $H_2SO_4$  in cycle are generated.

In brief, the process is the following:



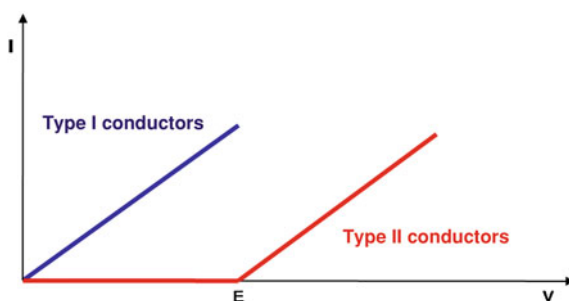
The *efficiency of the chemical plant* under consideration (defined by the ratio between the energy content of the hydrogen produced and the heat consumed) amounts to nearly 50%. The overall efficiency of the plant clearly depends on the efficiency of the heat production process.

Another chemical process, used in the plants in which heat is produced through solar concentrators, is based on the use of iron oxide as catalysts. The process is therefore the following:



Also in this case, the efficiency of the chemical plant is nearly 50%.

**Fig. 4.48** Typical voltage–current for type I and type II conductors



The use of concentration solar plants allows to reach very high temperatures, necessary for the dissociation reactions of the water molecule: in the focus of a parabolic mirror concentrating direct solar reactions, temperatures exceeding 2,000°C are reached.

Figure 4.47 shows the diagram of a solar thermolysis plant. The heat produced by parabolic concentrators is stored in suitable systems since the chemical plant must operate with continuity: in the periods of peak solar radiation, the heat produced is partly used to feed chemical plants, and partly stored. In the hours of absence of radiation, the chemical plant continues to operate, powered by the heat storage system.

Considering an efficiency of the heat collection and accumulation system amounting to 65% and an efficiency of the chemical plant of 53%, a global efficiency relating to hydrogen production from solar energy is obtained and amounts to nearly 35% [3].

## 4.2.7 Electric Power-to-Chemical Energy Conversion Plants

### 4.2.7.1 Electrolysis

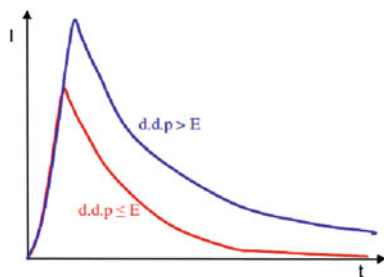
#### Overview on the Electrolysis Process

Electrolysis is a set of phenomena that take place in an electrolytic solution or in a molten electrolyte at the passage of electric current, usually continuous. In this way, the conversion of electric energy into chemical energy is made.

There are different ways of conducting current, and therefore it is possible to make a distinction between *Types I and II conductors*. In the case of the former, with the passage of continuous current, the Ohm's Law applies, whereas for type II conductors, the validity of this law is not a general one. Figure 4.48 shows the trends of current intensity according to the function of the difference of potential applied to a type I conductor and a type II one.

It is possible to see how in the case of a type II conductor only when the potential difference (PD) exceeds a given value ( $E$ ) a passage of current occurs,

**Fig. 4.49** Current plotted against time for different values of applied PD



which then increases proportionally to the PD applied until reaching a saturation state. Below this potential threshold there is not any passage of current and therefore there is no electrolysis. Electrodes in electrochemical processes are divided in different ways according to their characteristics and the ones of the electrolytic solutions. The latter exclusively represent catalyst elements of the electrode process and a typical example is the platinised platinum electrode.

Figure 4.49 shows the trend over time of current when an electrolysis cell with platinised platinum electrodes in contact with an electrolytic solution is imposed a PD.

If PD is lower than the threshold value  $E$ , it is possible to observe:

- *A first ascending phase:* in fact, at the beginning there is no PD among electrodes (identical electrodes in the same solution) and no electrode reaction occurs; however, in the moment in which the circuit is closed and the PD set is applied to electrodes, there is a passage of current and electrolysis takes place.
- *A second descending phase:* the molecules that during the passage of current are formed on the electrodes remain absorbed on them and let the cathode and the anode assume the nature of electrolytes relating to the species absorbed. In this way, inside of the electrolysis cell, a stack is generated, whose electromotive force-emf (as opposed to the PD imposed from the outside and also called *counter electromotive force—cemf*), opposes the passage of current. As the ionic species in the solution are exhausted at the electrodes, there is an increase in products' activity and the cemf increases, consequently determining the decrease of the intensity of the electrolysis current.
- *A third constant phase:* as the cemf becomes equal to the PD imposed from the outside, the passage of current basically stops, and remains constant at a value very close to zero.

With a progressively increasing PD, although always lower than  $E$ , the qualitative trend of the phenomenon does not change, but any increase of the PD imposed leads to an increase of the activities of electrolysis products on electrodes and therefore of cemf.

In this way, a value of pd imposed is reached, in which the activities of products and reagents becomes such that the pd is higher than cemf and the real electrolysis takes place, that is to say in the third constant previously described there is a passage of current.

The phenomenon described, based on which the electrodes of an electrolytic cell change their chemical nature on the surface during electrolysis, goes under the name of *chemical polarisation of electrodes*.

### Overvoltage

On the basis of the above, it follows that:

- If a PD lower than  $E$  (threshold) is applied to an electrolytic cell, there is no passage of current and therefore there is no electrolysis. This happens since there are conditions of equilibrium (between cemf and applied PD) and consequently the reaction speeds on electrodes are globally null.
- If the PD applied is higher than  $E$ , there are no more equilibrium conditions, the passing current has an intensity  $I$  and electrolysis takes place.

In order to have electrolysis, then, a PD higher than  $E$  must be applied, that is to say an overvoltage indicated as *intrinsic overvoltage* ( $V_i$ ), since it is implied in the phenomenon of electrolysis itself.

Another unavoidable increase of electrolysis PD, necessary to keep constant the value  $I$  of current, is due to the discharge of ions on electrodes, causing a decrease of concentration in the solution areas in contact with them, with subsequent migration towards those areas of other ions from the bulk of the solution (where concentration is higher). The slower the ion supply (for instance due to the high viscosity and/or low concentration of the solution), the more marked the concentration decrease in the electrode areas, the higher the cemf. This increase demands, in order to allow  $I$  to be constant, an equal increase of the electrolysis PD. In this way, there is another type of overvoltage, of concentration ( $V_c$ ), different from the one described above.

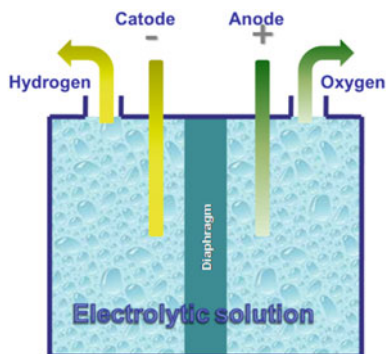
Finally, there is the increase of electrolysis PD due to the ohmic drop in the cell, whose value ( $V$ ) is given by the product of the electric resistance of the cell ( $\Omega$ ) by the intensity of the electrolysis current ( $A$ ); it varies with the distance between electrodes and with the resistance of the solution. This phenomenon represents the so-called *ohmic overvoltage* ( $V_h$ ).

Therefore, having called  $\Delta E_{\text{term}}$  the thermodynamic voltage, the PD needed for electrolysis is given by

$$V = \Delta E_{\text{term}} + V_i + V_c + V_h \quad (4.110)$$

In practice, in order to improve efficiency, the maximum reduction of the overvoltage has to be implemented. The intrinsic overvoltage is reduced by using catalysts (on the surface of the electrode), the concentration one by keeping the solution rough, and the ohmic drop by making electrodes as close as possible. Each reduction of  $V$ , in fact, represents an energy saving, an element which is very much important in the economy of industrial processes.

**Fig. 4.50** Diagram of an electrolytic cell

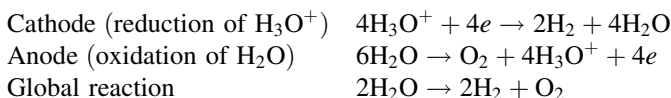


The phenomenon of electrolysis is governed by the Faraday's Law:

- The masses of chemical species formed (or consumed) to the electrodes during electrolysis are proportional to the quantity of electricity that has crossed the cell;
  - the masses of chemical species formed (or consumed) for the passage of the same quantity of electricity are, in whatever electrolysis, proportional to the equivalent masses of the species involved in electrolysis itself.
- The passage of 1 F in an electrolytic solution corresponds to the transformation (oxidation, reduction) of 1 equivalent of the chemical species that is electrolysed. Three different cases are possible:

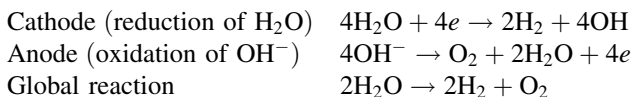
#### *Electrolysis of strongly acid solutions*

A solution of  $\text{H}_2\text{SO}_4$  with  $[\text{aH}_3\text{O}^+] = 1$  is taken into consideration. In this case it is possible to admit that  $\text{H}_3\text{O}^+$  ions, which are present in high concentrations at the cathode, are reduced and the  $\text{H}_2\text{O}$  molecules are oxidised at the anode, given the low concentration of  $\text{OH}^-$  ions. The electrode processes, therefore, are:

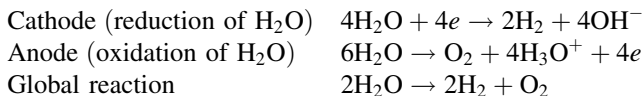


#### *Electrolysis of strongly alkaline solutions*

A solution of  $\text{KOH}$  with  $[\text{aOH}] = 1$  is taken into consideration. In this case, the following electrode processes take place:



*Electrolysis of neutral solutions* A solution of  $\text{K}_2\text{SO}_4$  is considered, since the  $\text{K}_2\text{SO}_4$  does not hydrolyse, the concentration of ions  $\text{H}_3\text{O}^+$  and of ions  $\text{OH}^-$  is small and the processes to the electrodes are:



In the three cases described, the global reaction is the same, and therefore the values of  $\Delta E = 1.23$  V coincide. Figure 4.50 shows the scheme of an electrolytic cell.

### *Electrolysis Efficiency*

The *efficiency of the electrolysis process* can be defined as the ratio between the electric power theoretically necessary to the process according to the Faraday's Law, and the one that is actually used. Indicating with  $F$  the Faraday constant, with  $z$  the number of electrons transported by each ion, with  $\gamma$  the speed (in mole/s) at which the reagent is consumed, the current,  $I_F$ , necessary to the process according to the Faraday's Law is:

$$I_F = z \cdot F \cdot \gamma \quad (4.111)$$

The necessary voltage according to the Faraday Law is  $\Delta E_{\text{term}}$ , therefore efficiency, indicating with  $V$  and  $I$  the effective voltage and current, is:

$$\eta = \frac{\Delta E_{\text{term}} \cdot z \cdot F \cdot \gamma}{V \cdot I} \quad (4.112)$$

Introducing the *voltage efficiency*  $\eta_V$ , defined as ratio between thermodynamic and real voltage:

$$\eta_V = \frac{\Delta E_{\text{term}}}{V} \quad (4.113)$$

And the *current efficiency*  $\eta_F$ , defined as the ratio between the Faraday current and the effective one:

$$\eta_F = \frac{z \cdot F \cdot \gamma}{I} \quad (4.114)$$

Replacing (4.113) and (4.114) in (4.112), the efficiency of the electrolysis process can be expressed as a product of the two efficiencies defined above:

$$\eta = \eta_V \cdot \eta_F \quad (4.115)$$

As already said, the thermodynamic potential of water electrolysis amounts to 1.23 V; however, considering the inevitable overvoltage, at least 1.4 V are necessary to obtain an acceptable reaction speed. In the current density conditions typical of commercial electrolyzers (amounting to nearly 1 A/cm<sup>2</sup>), there is a cell voltage between 1.7 and 2.0 V; current efficiency is close to the unit, thus to these values efficiencies of the electrolysis process of 60–70% correspond. As concerns

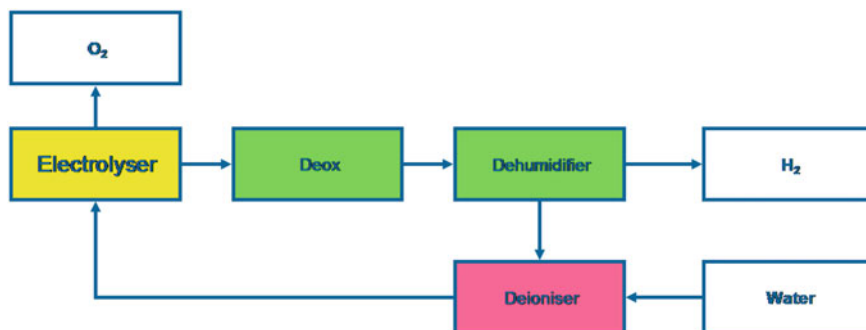


Fig. 4.51 Scheme of an electrolysis system

the efficiency of an electrolyser, auxiliary consumptions (mainly the pumping of hydrogen and oxygen) must be considered which cause, given the same hydrogen produced, an increase of electric power consumption by nearly 20%.

### Electrolysers

Figure 4.51 shows the chart of an electrolysis system; the electrolyser, fed with deionised water, produces hydrogen and oxygen. The hydrogen produced undergoes first of all a de-oxidation process and subsequently dehumidification to eliminate the (distilled) water present, which is then reused to fuel the electrolyser; at the outlet of the dehumidifier there is hydrogen with a very high degree of purity (>99.9%).

Water electrolysis always takes place in solution and not in pure water, since its conductivity would be very low and the current crossing the cell would be negligible; very often a basic solution of KOH (alkaline electrolysers) is used. As the concentration of the solution increases, two contrasting phenomena can be observed: on the one side, the number of charge conveyors increases (which improves conductivity); on the other side the interactions between ions which obstacle movement increase, hence leading to a decrease of the conduction movement. The maximum electric current in the cell is obtained with a concentration of the electrolytic solution of nearly 30%.

Electrolysers can be classified as follows:

- *Conventional alkaline electrolysers*: the concentration of the electrolytic solution (normally KOH) ranges between 20 and 30%, operating at temperatures ranging from 70 to 100°C and pressures between 1 and 30 bar;
- *Advanced alkaline electrolysers*: characterised by a lower distance between electrodes (which reduces the ohmic resistance of the electrolyte), by new techniques for the catalysation of active surfaces (which decrease overvoltage) and higher operating temperature;



**Table 4.7** Characteristics of conventional and advanced conventional alkaline

Parameter	Conventional	Advanced
Rated current density $J_t$ (A/cm <sup>2</sup> )	0.2	0.5
Superficial resistance $K$ (W/cm <sup>2</sup> )	1	0.4
Ohmic overvoltage (V)	0.2	0.2
Electrolysis overvoltage (V)	0.5	0.4
Cell rated tension (V)	2–1.8	1.78
Tension efficiency	0.747–0.83	0.839
Faradic efficiency	0.985	>0.99
Total efficiency (Ref. LHV)	0.62–0.70	0.71
Efficiency (ref.HHV)	0.74–0.82	0.83
Specific energy consumption (kWh/Nm <sup>3</sup> )	4.83–4.29	4.22

- *Solid polymer electrolyzers*: in which the PEM unifies the separator and electrolyte functions; they show potentially very high efficiencies (94%), but presently the actual efficiency is lower than the in alkaline ones and entail high costs;
- *Steam electrolyser*: the electrolyte is ceramic (ion conductor); the efficiency is potentially very high, but not yet available in the market.

Table 4.7 shows the main characteristics of conventional and advanced alkaline electrolyzers.

## 4.2.8 Radiant Energy-to-Chemical Energy Conversion Plants

### 4.2.8.1 Photoelectrolysis

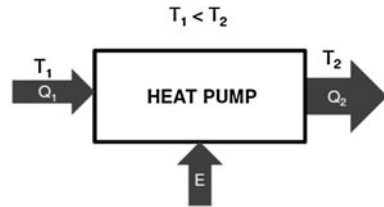
This process is based on the coupling of photovoltaic technology and electrolysis: in practice, these are electrolytic cells with electrodes in photovoltaic semiconductor material. The theoretical efficiency accounts for 45%, and experimentally it was possible to achieve efficiencies of 20% with amorphous silicon cells.

Solutions are under study which envisage the use of multilayer thin films that will reach efficiencies close to the theoretical one.

## 4.2.9 Electric Energy-to-Thermal Energy Conversion Plants

Through thermodynamic reverse cycles it is possible, by absorbing energy, to transport heat from a lower to a higher temperature, that is to say to decrease the heat of a room temperature source by refreezing it up to low temperatures. Usually, the energy that is absorbed by the systems that make these thermodynamic operations is electric. Among the plants that operate as recalled herein, there are *refrigerators* and *heat pumps*. In the formers, the main purpose is to refrigerate a

**Fig. 4.52** Operation scheme of a heat pump



body, that is to subtract heat from a body and reduce its temperature (from a few degrees above  $0^\circ\text{C}$  even up to cryogenic values of  $-250^\circ\text{C}$  and less). In the latter two different functions are possible: can be provide both heat and cool, for winter heating purposes as well as for summer conditioning.

#### 4.2.9.1 Compression Heat Pump

##### Overview

The *heat pump* is a machine able to transfer heat from a lower temperature room to another higher temperature area (Fig. 4.52). In general, the purpose is to heat a room at higher temperatures; sometimes the objective is to refrigerate a body at the lower temperature. Reversible heat pumps operate in both conditions, simply by changing the interval of operating temperatures.

The heat pump is made up of a closed circuit crossed by a fluid (refrigerant) with suitable characteristics that, according to its temperature and pressure conditions, takes a liquid or gaseous state, usually steam.

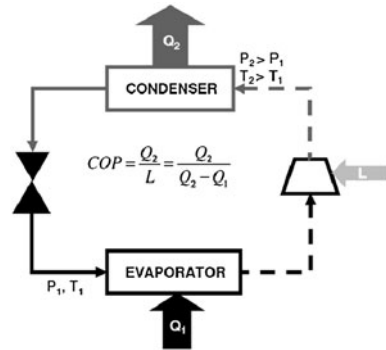
In its standard configuration, the closed circuit is made up as follows (Fig. 4.53):

- A compressor, C
- A condenser
- An expansion valve, V
- An evaporator

The condenser and the evaporator are two heat exchangers, namely two pipes in which a refrigerant fluid flows exchanging energy with a service fluid (either water or air). The refrigerant releases heat in the condenser and removes it in the evaporator. The components of the circuit can be grouped into a single block or divided into two parts (“split” systems) linked by the pipes in which the refrigerant fluid flows. In its operation, the refrigerant fluid, within the circuit, undergoes the following transformations (Fig. 4.54):

- *Compression* (1–2): the gaseous and low pressure refrigerant fluid, coming from the evaporator, is taken to high pressure during compression, and heats itself by absorbing a given quantity of heat.

**Fig. 4.53** Cycle of a compression heat pump



- *Condensation* (2–3): the refrigerant fluid, coming from the compressor, passes from the gaseous to the liquid state, releasing heat outside.
- *Expansion* (3–4): passing through the expansion valve, the refrigerant fluid partially transforms into steam and cools down.
- *Evaporation* (4–1): the refrigerant fluid absorbs heat from outside and evaporates completely.

The overall set of these transformations is the *heat pump cycle*: providing energy to the refrigerant fluid with the compressor, it absorbs heat from the surrounding medium in the evaporator and, through the condenser, releases it to the body to be heated.

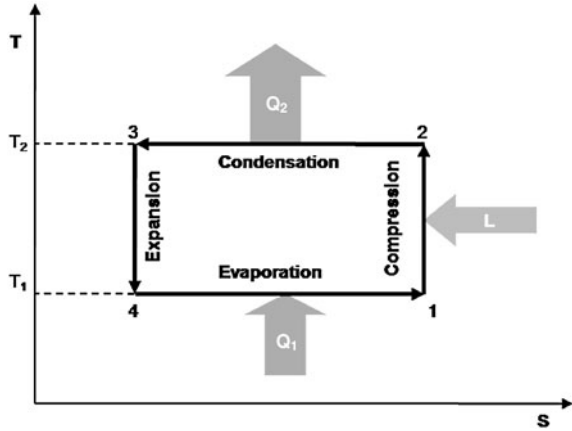
In the compression heat pumps, that are the far most widespread ones, the energy absorbed by the cycle ( $E$  in Fig. 4.52) is the mechanic energy necessary to activate the compressor; as it often happens, from an operative viewpoint, the energy supplied to the machine is electric power and the compressor is set in motion by an electric motor, therefore the plant, as a whole, operates a conversion from electric energy into thermal energy.

### *Thermodynamic Cycle*

While discussing about the thermodynamic cycle, reference will be made to compression heat pumps.

The phases of the cycle of a heat pump are shown in Fig. 4.53. The refrigerant fluid, at the liquid state and at a temperature  $T_1$  and pressure  $p_1$ , absorbs heat from the outside, evaporating; as it is known, the passage from one phase to another takes place at constant temperature and pressure. The steam is then taken to pressure  $p_2 > p_1$  through an adiabatic compression; therefore, the temperature at the exit of the compressor (which absorbs the mechanic work  $L$ ) will be  $T_2 > T_1$ . In these new conditions, the refrigerant fluid, at the gaseous state, releases heat to the outside by condensing at a temperature  $T_2 > T_1$ . At the exit of the condenser, the fluid is expanded adiabatically up to conditions  $p_1$  and  $T_1$  and the cycle starts again. Since the refrigerant fluid is at the liquid state, the (useful) work obtainable

**Fig. 4.54** The ideal thermodynamic cycle



in its expansion is absolutely negligible, therefore this expansion takes place in an expansion valve, that is to say the recovery of the expansion energy is given up.

Since expansion and compression are adiabatic transformations, and the passages of phase (evaporation and condensation) are isothermobaric, the reference thermodynamic cycle is the Carnot cycle, shown in Fig. 4.54, considering the fluid as a perfect gas and the ideal transformations the reversible ones.

From Fig. 4.53, it is possible to determine the energy balance of the cycle as follows:

$$Q_2 = Q_1 + L \Rightarrow L = Q_2 - Q_1 \quad (4.116)$$

If  $Q_2$  is the *useful effect* (heating) the *coefficient of performance* (COP) is the ratio between the useful effect and the energy supplied from the outside. Therefore, having considered (4.116), it follows that:

$$\text{COP} = \frac{Q_2}{L} = \frac{Q_2}{Q_2 - Q_1} \quad (4.117)$$

With regard to Fig. 4.54 we have:

$$Q_2 = T_2(S_3 - S_2) = T_2 \cdot \Delta S \quad (4.118)$$

$$Q_1 = T_1(S_3 - S_2) = T_1 \cdot \Delta S \quad (4.119)$$

By replacing (4.118) and (4.119) in (4.117), it follows

$$\text{COP} = \frac{T_2}{T_2 - T_1} \quad (4.120)$$

The refore, the COP, depends on the limit temperatures of the cycle and decreases as the difference between the two temperatures increases.<sup>30</sup> Considering,

<sup>30</sup> For this reason, heat pumps are more suitable for mild climate.

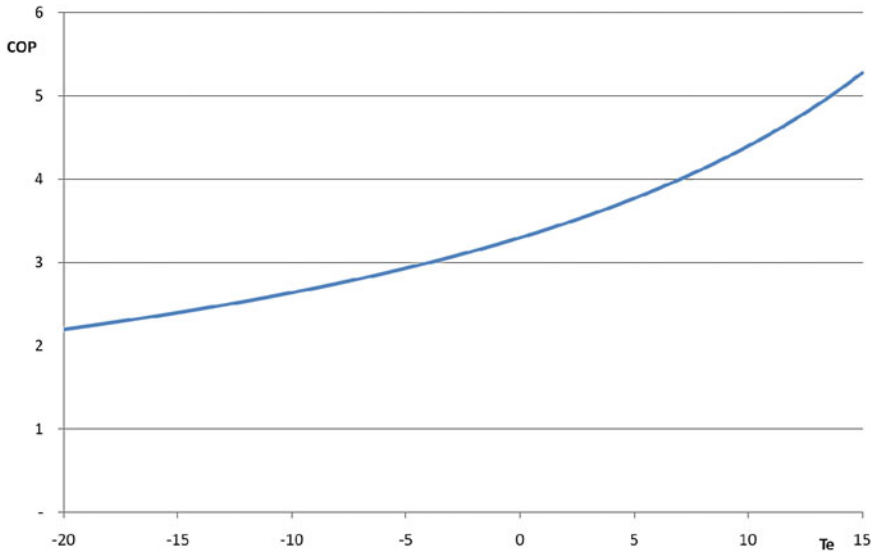


Fig. 4.55 COP of a heat pump as the external temperature varies

for instance,  $T_1 = 5^\circ\text{C} = 278\text{ K}$  and  $T_2 = 20^\circ\text{C} = 293\text{ K}$  a  $\text{COP} = 18.3$  is obtained.

For the calculation of the real value of the COP, it is necessary to consider the actual operating conditions.

First of all, as concerns the previous example, the external temperature amounts to  $5^\circ\text{C}$ , and the temperature of the fluid at the evaporator  $T_2$  must be lower, to allow the thermal exchange between the external source and the fluid itself. Similarly, if the internal temperature is  $20^\circ\text{C}$ , the temperature of the fluid at condenser  $T_1$  must be higher. Considering, for thermal exchanges, a  $\Delta T$  of  $10^\circ\text{C}$ , then  $T_1 = -5^\circ\text{C} = 268\text{ K}$  and  $T_2 = 30^\circ\text{C} = 303\text{ K}$ . With these values, a  $\text{COP} = 7.7$  is obtained.

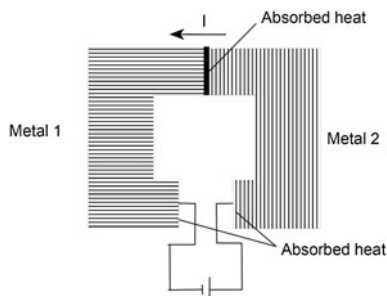
Furthermore, it is necessary to consider the real transformations of the thermodynamic cycle: the real compression work  $L_r$  is higher than the ideal work  $L_i$ , being:

$$L_r = \frac{L_i}{\eta_c} > Q_2 - Q_1 \quad (4.121)$$

where  $\eta_c$  is the *compression thermodynamic efficiency*. Furthermore, the electric energy consumed for compression ( $L$  in Fig. 4.53) is higher than the real work since it is necessary to consider the *efficiency of the electric motor*  $\eta_{\text{ME}}$ :

$$L = \frac{L_r}{\eta_{\text{ME}}} = \frac{L_i}{\eta_c \cdot \eta_{\text{ME}}} = \frac{Q_2 - Q_1}{\eta_c \cdot \eta_{\text{ME}}} \quad (4.122)$$

**Fig. 4.56** Diagram for the study of the Peltier effect



Furthermore, considering the load losses (during expansion, in the condenser and in the evaporator) and the efficiency of the compressor, the COP values amount to nearly 3–5, and obviously vary as the operating temperatures vary, as it is shown in Fig. 4.55.

As previously said, the heat pump can also have the feature of refrigerating or cooling. In this case the thermodynamic cycle remains unchanged; what changes is only the interval of operating temperatures (if the purpose is heating, the maximum temperature will be, for instance,  $45 \div 50^\circ\text{C}$ ; for refrigeration, it will be close to room temperature, having considered that the purpose in this case is to keep temperature  $T_1$  lower than the room one).

From the plant and the thermodynamic viewpoint, the same considerations apply: in this case the useful effect is the heat absorbed during condensation ( $Q_2$ ). The COP value of cooling is normally lower than the one obtained in heating.

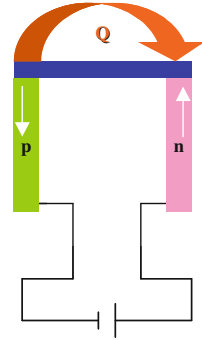
In conditions of partial load, if the compressor, set in motion by an electric motor, works at a constant number of revolutions, then the compression efficiency (and, therefore, the COP) falls suddenly. The use of inverters, that change the frequency of the supply current of the electric motor, allows to vary the number of revolutions of the compressor, so obtaining a good efficiency also in the operation with partial loads.

#### 4.2.9.2 Peltier Effect Heat Pumps

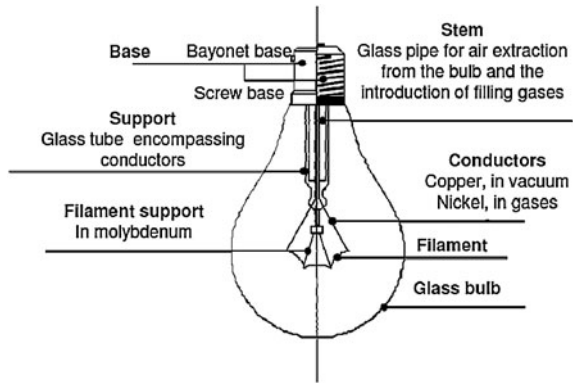
This type of heat pumps operates on the basis of the *Peltier effect*. To briefly recall the characteristics of this effect, one can refer to Fig. 4.56, in which a thermoelectric circuit is connected to a battery that allows direct current  $I$  to flow in. As it is known, two different metals have free electrons at different levels of Fermi,<sup>31</sup> characterised by separate values of kinetic energy and concentration; as a consequence of this, at the contact of the two metals the *e.m.f.* allows each electron that crosses the interface to deliver a given quantity of energy (positive in one

<sup>31</sup> At absolute zero the *Fermi level* or *Fermi energy* is, at absolute zero, the highest energy level occupied by the “free” electrons of the conduction band. It is typical of the material considered and weakly depends on temperature. At higher temperatures, some free electrons can be at higher levels, according to the statistical distribution function provided by the Fermi–Dirac theory.

**Fig. 4.57** Diagram of a Peltier effect heat pump



**Fig. 4.58** GLS incandescent lamp [4]



direction, negative in the other). This energy exchange translates into a heat absorption in one of the junctions and into release in the other.

The electric power  $W_p$  developed and absorbed in each junction is given by the ratio:

$$W_p = \alpha_{P_{1,2}}(T) \cdot I \quad (4.123)$$

where  $\alpha_{P_{1,2}}(T)$  is the *Peltier coefficient*. It has the same physical mean of a *e.m.f* and, depends on the materials used and varies according to temperature. If dependency upon temperature is put aside<sup>32</sup>, then the quantity of heat absorbed in a time unit at a junction is exactly the same as the one developed at the other.

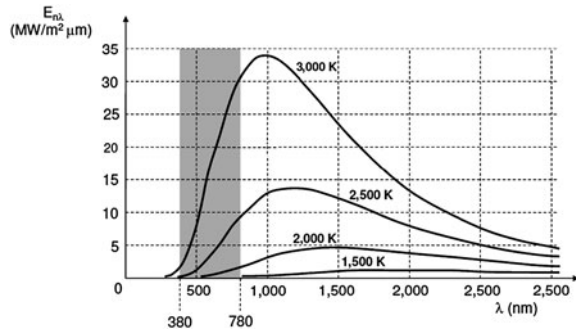
It is useful to consider the Peltier coefficient as follows:

$$\alpha_{P_{1,2}} = \alpha_{P_1} - \alpha_{P_2} \quad (4.124)$$

By convention, the Peltier coefficient is positive if heat is absorbed when the current flows from the material with a Fermi level higher than the one with the lower level 0.

<sup>32</sup> This admission does not introduce a significant error.

**Fig. 4.59** Spectrum of emission of the black body



The Peltier effect can be exploited for the carrying out of heat pumps; in these applications, electric current is circulated in a circuit as the one shown in Fig. 4.56: exploiting as a “useful effect” the passage of heat from one junction to the other.

Figure 4.57 shows the scheme of this type of heat pump: the use of semiconductors imposes the adoption of low voltages and, therefore, given the same power, high currents; to avoid too high currents, several cells in series must be connected. In any case, this type of heat pumps is only used for small powers. The COP is low (1.2–1.4) and markedly decreases as the difference of temperature increases: therefore, to obtain acceptable values of COP, the temperature difference between the hot joint and the cold joint shall not exceed 20°C.

### 4.2.10 Electric Power-to-Radiant (Luminous) Energy Conversion Plants

#### 4.2.10.1 Incandescent Lamps

##### GSL Incandescent Lamps

Historically, incandescent lamps are the previous ones and nowadays are still the most widespread; their success over time is due to the good compromise they make between mean life, luminous efficiency and price.

The most common model of incandescent lamps is represented by *general lighting service* (GLS) lamps (Fig. 4.58). The first patent of these lamps dates back to Edison, in 1841, but it was only in 1880 that they were actually commercialised.

They are made with a base and a glass bulb inside of which there is a filament that, when the lamp is connected to a power circuit, is crossed by an electric current that heats it until reaching incandescence, leading it to emit radiant energy including different wavelengths. The filament emission is regulated by the Planck’s Law, since in general it is a material similar to a high-emission black or grey body (Fig. 4.59). Therefore, it emits on the entire spectrum, for wavelengths between 0 and  $\infty$ , and the emission decreases until becoming null for  $\lambda = 0$  and  $\lambda = \infty$ .



According to the Wien's Law, the maximum emission is obtained when:

$$\lambda_{\max} = \frac{2.9 \times 10^6}{T} \quad (4.125)$$

As temperature increases, this maximum moves from the infrared ( $T = 1.500$  K) to the field of visible light ( $T = 3.000$  K). In particular, in order to have it at  $\lambda = 555$  nm, to which corresponds the maximum level of visibility, it is necessary that the filament reaches a temperature of 5,225 K, too high for whatever known material: therefore, in practice, the maximum emission mainly occurs in the field of infrared radiation. In the first models, until 1913, the filament was linear and made up of coal; it worked at nearly 1,800°C, since it was not possible to reach higher temperatures in order to avoid the *sublimation of carbon*. This phenomenon must be generally avoided for two reasons: because it produces a too rapid destruction of the filament that, in losing matter, weakens and breaks, and because of the subsequent deposit of the vapours released on the internal surface of the glass bulb darkening it and therefore decreasing the transparency of the glass and, subsequently, the luminous flow emitted outside.

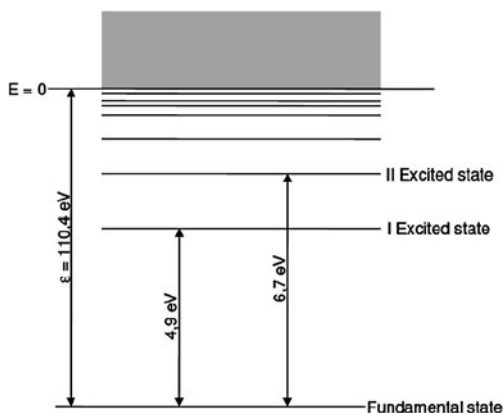
At 1,800°C the maximum emission is at  $\lambda = 1,400$  nm, whereas only a small portion of the radiation energy falls in the field of visible radiations. Furthermore, the lamps work with very low pressures in the bulb: in fact, the vacuum was created in it to delay the oxidation of the filament and prevent it from burning; however, the low pressure had, together with high temperature, the unwanted effect of *accelerating carbon sublimation*. This problem has represented for a long time a limitation to temperature increase, since it was kept very much below the melting temperature, until tungsten was adopted, once all the techniques necessary for its processing in rather thin wires of suitable electrical and mechanical characteristics were fine-tuned.

This material, due to its very high melting point (3,770 K), allows to reach very high temperatures (it should not exceed 2,500°C in vacuum and 2,800°C in inert gas), hence guaranteeing high-energy emissions with wavelengths that fall in the visible light.

Furthermore, it shows outstanding features in terms of ductility and electric and mechanical resistance, which allow in the lamps that are presently available in the market, differently from the first types of products, to coil it up in a double-helix shape to increase its mechanical resistance and allow a minimum heat dispersion.

In case of powers exceeding 25 W, inert gases are generally introduced in the bulb, usually argon and nitrogen mixes (but also, in case of special applications, krypton or hydrogen) that reduce the sublimation of the filament, although in this way a certain heat transmission is activated by convection between the filament, the gas and the glass, which lowers the temperature of the filament and subsequently reduces its efficiency. In general the best filling gas is krypton since, besides having a sufficient chemical inertia, it also shows a low value of thermal conductivity.

**Fig. 4.60** Diagram of the energy levels in mercury atom

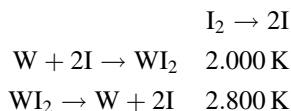


Incandescent lamps are however characterised by a heat emission that clearly prevails compared to the one of luminous radiations, and for this reason they have a limited efficiency, which varies between 10 and 20 lm/W, with higher values for greater powers. Their mean life is nearly 1000 h, with a final luminous flow accounting for 87% of the initial one. The colour temperature coincides with the filament temperature which is variable from 2,700 to 3000 K. To increase its value, the glass of the bulb is generally coloured in light blue: in this way it is possible to obtain a less reddish light that is more suitable for some applications. However, in doing so, the luminous flow emitted is reduced—as it is partly absorbed by the coloured glass—as well as efficiency.

#### *Incandescent Halogen Lamps*

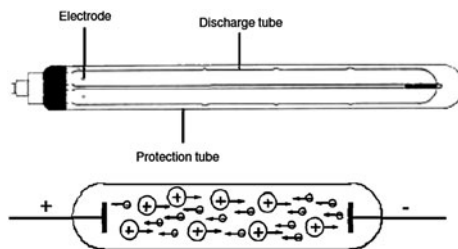
A further development of this type of light source is represented by *halogen lamps*, in which a small quantity of halogen gas (generally iodine, bromine or chlorine) is inserted in the bulb to effectively counter the evaporation of tungsten.

The presence of these substances, in addition to inert gases, allows the triggering of a regenerative cycle of tungsten, given by the following reactions:



In the area of the lamp with the lowest temperature, the vapours of tungsten freed from the filament are chemically combined with the iodine present, forming gaseous tungsten iodine ( $\text{WI}_2$ ) or other similar compounds. This compound, while migrating to the area of the hot filament, decomposes in its elements, forming metallic tungsten that newly deposits on the filament. In this way, most of the sublimated tungsten deposits once again, markedly slowing down both the erosion process of the filament and the deposition on the inside of the bulb.

**Fig. 4.61** U-shaped discharge tube filled with low-pressure gas [4]



Furthermore, in these conditions the filament can be crossed by a more intense current, allowing to reach higher temperatures ( $\sim 3200$  K) and subsequently higher flows (this entails, however, that the bulb consists of quartz glass, in consideration of its capacity to resist to the high temperatures to be reached); therefore, there is an increase both in the luminous efficiency, that is on average 25 lm/W, but which can also reach 30 lm/W, and the colour temperature (white light). The colour-rendering index amounts to 100, the mean life is 2,000 h, and the final luminous flow is 94% of the initial one. For their particular characteristics, these lamps find application both in interior lighting, and in exterior lighting in case of large complexes, for photograph shooting, in the headlights of vehicles, etc.

#### 4.2.10.2 Gas-Discharge Lamps

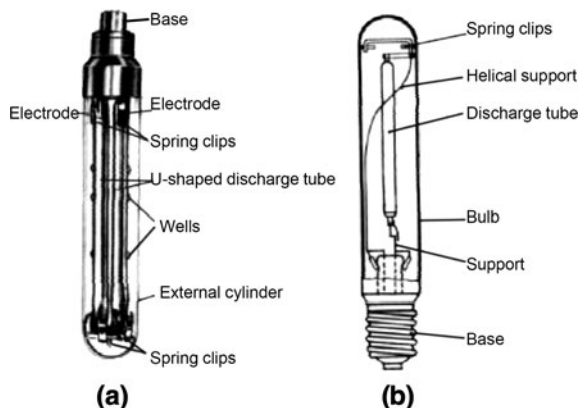
In discharge lamps, light production is due to the emission of luminous radiations by a preventively excited gas<sup>33</sup>: when an electron goes back to its orbit, luminous energy is emitted in the amount of the difference of energy between the two states. Since electronic orbits are defined, energy gaps are defined as well and typical of the gas filling the bulb; to a given energy corresponds therefore a well-defined wavelength and therefore a precise colour (Fig. 4.60). Consequently, these sources emit a light made up of the typical radiations of gas, and the spectrum is discontinuous (with lines).

Differently from incandescent lamps, in which the light emitted can be considered as a by-product of the transformation of electric power into thermal energy, in the discharge ones the light is obtained through the *direct transformation of electric power into luminous energy*. For this reason they are characterised by a light efficiency far higher than the filament ones, ranging between 35 and 200 lm/W. The mean life as well is higher than incandescent lamps and varied between 5,000 and 12,000 h according to the type of lamp. Conversely, generally these lamps do not meet in the same way the colour rendering<sup>34</sup> requirements.

<sup>33</sup> Excitation consists in the removal of electrons from the stable orbit, made by other electrons accelerated by an electric field.

<sup>34</sup> Due to the fact that these sources emit a light whose spectrum is discontinuous.

**Fig. 4.62** Low pressure  
(a) and high pressure  
(b) sodium lamp [4]



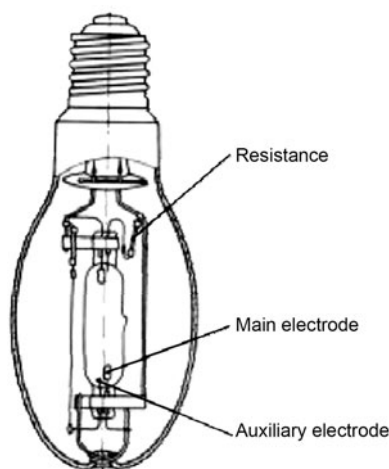
They are essentially made up of a container, generally in glass or quartz with two electrodes, in which a gaseous body is fit (metallic vapours, sodium or mercury in particular, since the radiations they emit are found in the visible spectrum, xenon or rare gases) at a suitable pressure (Fig. 4.61).

Sodium in particular, being solid at the ordinary temperature, must pass to the gaseous state to be able to emit: therefore it is plunged in a neon atmosphere which allows the triggering of the discharge and the necessary temperature increase. According to the value of pressure of the discharge pipe, this type of lamp can, in turn, be divided into two sub-groups: *high* and *low pressure*. In low-pressure sodium steam lamps (0.5 Pa) the discharge takes place in a glass U-shaped pipe, protected by an external glass tubular bulb, whose internal surface is covered with indium oxides to ensure a good thermal insulation, having considered that the lamp works better at high temperatures (270°C) (Fig. 4.62).

At low pressures, sodium emits a practically monochromatic yellow light (a doublet of yellow-orange spectral lines, very close to the maximum light sensitivity, at 589 and 589.6 nm), and cannot be used for internal lighting and for all those applications in which the distinction of colours is important: for this reason, their use is destined to those cases in which colour rendering is not important; in particular, in Italy this lamp is mostly used for road lighting. Light efficiency in low-pressure lamps reaches 200 lm/W, whereas their mean life ranges between 8,000 and 10,000 h. Colour rendering is obviously completely insufficient ( $R_a = 0$ ): in particular the low-pressure sodium lamps are disadvantaged from this viewpoint. In high-pressure sodium lamps (40 kPa) the discharge still takes place at high temperature, with the emission on a line spectrum or continuous spectrum in the visible light, therefore the colour is not monochromatic yellow any longer, but rather white-gold ( $R_a = 60$ ) with a colour temperature varying from 2,200 to 4,200 K (Fig. 4.62).

The luminous efficiency is slightly lower than the one obtained at low pressure, in any case exceeding 100 lm/W. Its lifetime goes from 5,000 to 12,000 h, and the flow at the end of the useful life is reduced on average to 90% of the initial one.

**Fig. 4.63** Very high pressure mercury steam lamp [4]



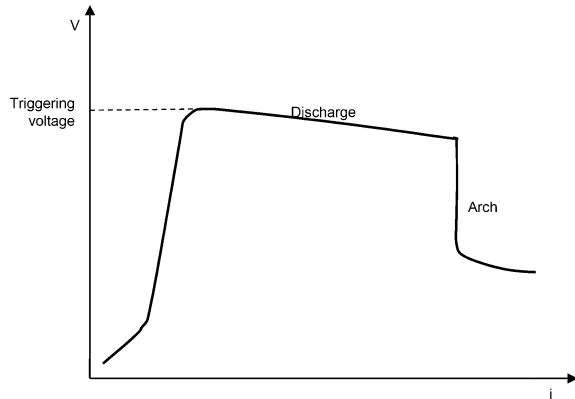
On the contrary, at a low pressure mercury usually has an emission spectrum characterised by a doublet of lines placed in the ultraviolet area (254 and 185 nm), whereas at high pressure there are other lines in the field of the visible light (blue, green); with the further pressure increase, the lines widen into bands and the emission spectrum becomes a continuous one, although lacking in the wavelengths corresponding to red. Therefore low pressure bands are not used for lighting purposes, but rather for particular technological operations that require the use of UV radiation. Their widespread use is possible, in fact, only after correcting the quantity of light emitted, as it happens in fluorescent lamps.<sup>35</sup>

Efficiency in high-pressure lamps is relatively low and ranges from a minimum of 35 lm/W to a maximum of 50 lm/W. Also the colour-rendering index ( $R_a = 60$ ) and the colour temperature (2,150 K) are relatively low, and this explains the present low use of these lamps (in the case of street lighting, they have been almost entirely replaced by the sodium-vapour ones). In some types of lamps, sodium halide (hydride), thallium and indium are added to correct the characteristics of the emission spectrum and to improve the light efficiency, which can reach 95 lm/W. These lamps are able to cover the same market of halogen lamps and fluorescent lamps, with the advantage compared to the former of a higher efficiency and to the latter of the availability of higher flows.

In order to improve colour rendering ( $R_a = 65\text{--}80$ ) recently small halide lamps were produced with the addition of holmium, dysprosium, etc., comparable to halogen lamps but with the advantage of a 2/3 energy saving. These are in practice discharge lamps miniaturised with a luminance of 15 Mcd/m<sup>2</sup>, whose colour temperatures range between 3,000 and 6,000 K, and with a mean life exceeding even 6,000 h. Finally other discharge lamps use a xenon atmosphere, which allows

<sup>35</sup> See Sect. 1.2.10.2.1.

**Fig. 4.64** Voltage–current characteristic curve in a discharge tube



to obtain emission spectrums that reproduce, with a good approximation in the visible field, the one of solar radiation. It follows a faithful rendering of colours, and therefore these lamps are well used for the lighting of indoor and outdoor areas.

A brief mention is finally deserved by very high pressure mercury vapours (3.5–10 MPa), with very high luminance (100,000 stilb) and are mostly used in scientific laboratories (Fig. 4.63).

The gas discharge phenomenon can be described as follows. In a mass of rarefied gas there are always free electrons due to photoelectric effects or to a cosmic radiation. At ordinary temperatures, the energy owned by molecules ( $3kT/2$ ) is of the same magnitude as the energy exchanges among molecules or between electrons and molecules caused by their collisions.

If however temperature is analysed or if particles are accelerated with a suitable electric field, then there are the conditions for the ionisation of gas and the subsequent phenomena that are at the basis of the operation of a discharge lamp. In particular, when the two electrodes are connected to a source of direct voltage the characteristic curve  $V(I)$  is diagrammed, then it follows that (Fig. 4.64): for very low values of gas, which usually has a very low thermal conductivity, it acts as a perfect insulator; in these conditions there is only a weak passage of current due to the free electrons that are present and near the first section of the curve there is a trend of growing  $i$  with  $V$ .

For the highest voltage values, electrons will acquire kinetic energy according to the electric field existing between electrodes, moving towards the anode and colliding in their pathway against gas atoms. A collision occurring at low speeds is elastic and causes the deviation of the collision electron, which releases a small part of its kinetic energy to the gas atom that is heated.

On the contrary, as speed increases, the quantity of energy exchanges caused by the collision between particles increases; consequently the likelihood of determining the ionisation of a molecule. A collision taking place at high speeds causes the change of orbit of one of the external electrons to a higher energy level, exciting the atom. After a very short time, ranging between  $10^{-9}$  and  $10^{-8}$  s, the

electron goes back to its initial level and in passing from a higher energy status  $E_2$  to a lower one  $E_1$  the atom emits a quantum of light (photon) amounting to the difference:

$$E_2 - E_1 = h \cdot \nu \quad (4.126)$$

with  $h$  as Planck's constant ( $6.63 \times 10^{-34}$  Js) and  $\nu$  as frequency of the emitted radiation (in  $\text{s}^{-1}$ ). Since the energy released by the electron with the collision amounts to eV, the wavelength of the photon emitted will be given by:

$$\lambda = \frac{c}{\nu} = \frac{c \cdot h}{e \cdot V} \quad (4.127)$$

When finally the collision takes place at a speed so high that a peripheral electron is taken away from the atomic system, the atom is charged positively and therefore it ionises. The freed electrons behave exactly like a colliding electron, whereas the ion can recombine with another electron producing light, or release heat through collision against the walls. If an appropriate continuous voltage is applied to the discharge tube, there will be a continuous formation of ions moving towards the cathode and a production of other electrons that will very quickly move towards the anode. In the characteristic curve of the tube, this phenomenon turns into a rapid increase of current as voltage increases. Under the bombardment of ions, the cathode heats and emits in turn electrons due to the thermionic effect: therefore the ionisation increases and a number of electrons is produced that is sufficient to allow the discharge to become independent from the original free electrons (in this case it is generally said that it is self-sustained). The gas has become in this way a conductor, the voltage drop on the lamp decreases and the current increases. The minimum voltage able to trigger this process, that corresponds to the voltage at which the lighting of the lamp takes place, is called in fact *triggering voltage*.

In the typical curve there is then a section of negative resistance (corresponding to the operation of discharge lamps) in which the potential drop between electrodes decrease as current increases. The voltage at the terminals sufficient to keep the discharge is lower than the triggering voltage. Another section corresponding to the disruptive or arch discharge finally follows that is only exploited for arch lamps, used in special applications.

The trend of the curve (triggering voltage, arch voltage, etc.) depends on the form of the tube and on the nature of gas. In particular, the triggering voltage depends on the product of pressure by the distance between electrodes (Paschen's Law), therefore the higher their values, the higher it will be: this can be explained by making the following considerations.

At high pressures the *mean free time* (the time between the two subsequent collisions) is rather short, therefore they do not succeed in gaining a sufficient kinetic energy to produce the ion ionisation in collisions. Only by increasing the pd at the terminals it is possible to suitably accelerate the particles in such a way as to

allow collisions to have the ionisation of other atoms: this translates, therefore, into an increase of the value of the triggering voltage.

At low pressures, when the gas is very much rarefied, the mean free time is much larger, therefore the possibility of having a collision before the accelerated particle reaches the opposite electrode is rather low. Also in this case, only by increasing voltage it is possible to reduce the mean free time producing a higher agitation of particles and this, once again, translates into an increase of the triggering voltage.

Furthermore, for a given gas and at a given pressure, the triggering pressure increases as the diameter of the tube decreases. This can be explained by observing that a small diameter facilitates the possibility of ion and electron recombination on lateral surfaces before causing other ionisations. The value of the triggering voltage can however be reduced by using both *rare gases*, and *appropriate electrodes*. The former show an excitation voltage very close to their ionisation voltage, which facilitates the definition of the discharge through the gas (furthermore these gases, as all the metallic vapours, have a monatomic molecule, and this allows not to disperse energy in the collisions with electrons to excite oscillations and rotations of the atoms of the molecule). As to the appropriate electrodes, it is possible for instance to coat the cathode, which is generally made in tungsten, with layers of alkaline-terrous oxides, such as BaO, SrO and CaO, with a low exit potential, which facilitate ionisation phenomena). It is also possible to adopt auxiliary electrodes, that is to say the heating of electrodes.

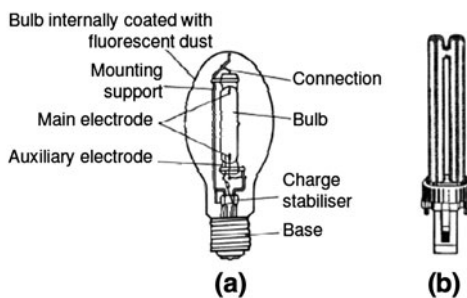
In order to allow the phenomenon of the discharge not to be exhausted, it is necessary that the gas remains ionised, with shifts towards the cathode of positive ions and of electrodes towards the anode. In this way a progressively higher current is however determined, which must be stabilised by using some *current limiters*, called *reactors*, inductive ballast resistors that are used to limit power drops.

## Fluorescent Lamps

To exploit the emission of ultraviolet radiations by some gases and vapours (mainly mercury) used in the discharge tubes (that, exception made for specific applications, is unusable) in this type of lamps the phenomenon of fluorescence is exploited, a property that some substances have in terms of absorbing small wavelength electromagnetic radiations and releasing energy in the form of higher wavelength. This phenomenon allows the recovery of the energy emitted outside of the visible, also allowing the correction of the colour of the light emitted, with a very high colour rendering. It is based on the property owned by some substances called *phosphor* of exciting when they are invested by a radiation, emitting in turn energy radiations with a lower energy than the excitement one, and therefore of a higher wavelength. The emissions stop within a very short period of time ( $10^{-8}$  s) from the interruption of the exciter radiation. With these substances, that are made



**Fig. 4.65** Mercury vapour (a) and compact (b) bulb fluorescent lamp [4]



up of oxysulphide, aluminates, phosphate tungstate and silicate of Calcium, Magnesium and Zinc, associated to heavy metals as copper or antimony, the internal surface of the glass cover is therefore involved (Fig. 4.65). Furthermore, very often in fluorescent salts the particular traces of substances called *activators* are dispersed.

A similar phenomenon often consistent with fluorescence is furthermore *luminescence* or *phosphorescence*, that is conversely extended in time. The colour of the resulting light varies with the nature of phosphors and of activators, and goes from hot white ( $\approx 3.000$  K), that is close to the colour of the light emitted by incandescence lamps, up to the white-light blue of the daily light (temperature of colour  $\approx 6.500$  K). Tubular fluorescent lamps are on the contrary generally filled with argon, with the addition of a small quantity of mercury, in order to facilitate the triggering of the discharge. A common characteristic of this type of lamp is the low luminance of the emitting surface ( $4,000\text{--}7,000$   $\text{cd/m}^2$ ): this feature sometimes makes it possible for the use of these sources without any direct shielding to avoid glare, as it is conversely necessary with other types of lamps.

In consideration of the capacity of these lamps to recover energy, the luminous efficiency is generally very high ( $85\text{--}95$   $\text{lm/W}$ ). Their mean life is nearly 10,000 h, whereas the final luminous flow accounts for 85% of the initial one. The colour-rendering index is included between 85 and 95.

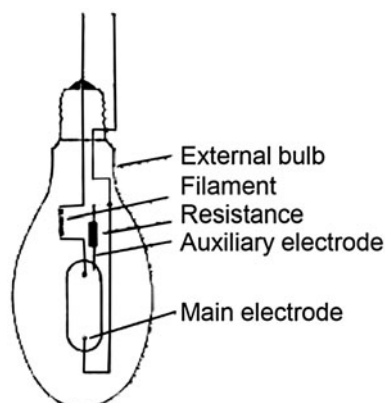
Additionally, in the last few years small-sized fluorescent lamps were produced, which are destined to the same market as incandescent ones, of which they basically offer the same chromatic quality of light ( $R_a = 85$ ), allowing however considerable energy savings (Fig. 4.66).

Their cost, still higher compared to incandescent lamps, is in fact offset by a higher efficiency ( $50\text{--}80$   $\text{lm/W}$ ) and a longer mean life (6,000 h).

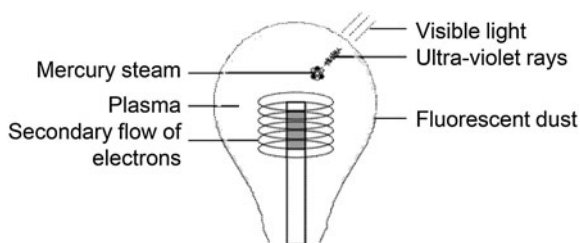
### Mixed-Light Lamp

These are mercury vapour bulb fluorescent lamps, where inside of the bulb, a filament of tungsten is added and connected in series to the discharge tube (Fig. 4.66). The filament, in emitting through incandescence with its continuous

**Fig. 4.66** Mixed-light lamp  
[4]



**Fig. 4.67** Operation diagram  
of an induction lamp [4]



spectrum rich in large wavelength radiations, offers a useful contribution to the production of the luminous flow and improves colour rendering. A further advantage is given by the fact that these lamps do not require any reactor. The values of luminous efficiency are intermediate between incandescent lamps and fluorescent lamps (20–30 lm/W), the colour temperature is around 3,000–4,000 K, the colour-rendering index goes from 40 to 75 and the mean life from 5,000 to 7,500 h.

### *Induction Lamps*

These are new generation lamps, whose functioning is based on the fluorescent lamps, but in which electrodes are eliminated since they represent the weak point in terms of duration. The power requested is in this case provided by a high-frequency electronic generator (2.65 MHz) that, once coupled with a coaxial cable to an antenna, creates an alternate magnetic field that in turn induces a secondary electric field (Fig. 4.67). Therefore, an induced current is generated which circulates in the mix of mercury vapour and rare gas contained in the bulb, triggering the ionisation phase previously described.

The efficiency is around 65 lm/W, the colour temperature around 3,000–4,000 K, the colour-rendering index is higher than 80 and the estimated mean life is 60,000 h.

**Table 4.8** Energy transformation processes

Conversion	Plant	Conversions and transformations
Chemical	Reformer	Conversion of fuel's chemical energy to be reformed into thermal energy Conversion of thermal energy into chemical energy of the fuel produced
	Partial oxidation	Conversion of fuel's chemical energy to be reformed into thermal energy Conversion of thermal energy into chemical energy of the fuel produced
	Gasification	Conversion of fuel's chemical energy to be reformed into thermal energy Conversion of thermal energy into chemical energy of the fuel produced
	Pyrolysis	Conversion of fuel's chemical energy to be reformed into thermal energy Conversion of thermal energy into chemical energy of the fuel produced
	Fermentation and digestion	Direct transformation
	Photoproduction	Direct transformation
Heat	Absorption heat pumps	Direct transformation

### 4.3 Energy Transformation Plants

Also in the case of *transformation plants* aimed at producing energy vectors, the same concepts and criteria exposed for conversion plants apply. In general, in a plant, different energy transformation and conversion processes take place that allow to transform the resource used into the desired form of energy. For instance, in the steam reforming process there is also a conversion of chemical energy into thermal energy (part of the fuel to be reformed to produce hydrogen is burnt to produce the necessary heat to trigger reactions); the heat produced is in turn converted into chemical energy. Therefore, globally, *a steam reforming plant operates a transformation of chemical energy*, producing a fuel with given characteristics starting from a different fuel with different characteristics.

Table 4.8 shows the transformation plants tackled in this paragraph.

#### 4.3.1 Chemical Energy Transformation Plants

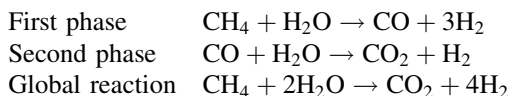
##### 4.3.1.1 Steam Reforming

This process, which since the mid-60 ranks first in the industrial preparation of hydrogen (presently, the most cost-efficient, the most common and with the highest efficiency), is based on the reaction of a hydrocarbon (mainly methane)

with water vapour according to the reaction  $\text{CH}_4 + \text{H}_2\text{O} \leftrightarrow \text{CO} + 3\text{H}_2$ . This is an endothermic reaction and the relevant balance, at low temperatures is heavily shifted to the left side. Therefore, this reaction is carried out at high temperatures (nearly  $800^\circ\text{C}$ <sup>36</sup>), in the presence of catalysts (nickel salts supported on aluminium oxide), and at a pressure of nearly 30 bar.

The  $\text{CO} + 3\text{H}_2$  mix produced, also containing low percentages of  $\text{CO}_2$ ,<sup>37</sup> is indicated with the name of water gas, is then subtracted from the equilibrium, enriched with a suitable quantity of water steam and passed through catalysts (with iron and cobalt) at temperatures of nearly  $400^\circ\text{C}$  (shift reaction). In this way there is a reaction called *water gas conversion reaction*  $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$ .

In brief this process, with a global efficiency of around 75%, will be:



In the ideal case, as it can be derived from the global reaction, there is the emission of 1 mole of  $\text{CO}_2$  for every 4 mole of hydrogen produced. Considering molar weights, there are 5.5 g of  $\text{CO}_2$  for every g of hydrogen produced. As concerns the methane produced, there is the emission of a mole of  $\text{CO}_2$  for every mole of  $\text{CH}_4$  consumed, that is to say 2.75 g of  $\text{CO}_2$  every g of  $\text{CH}_4$  consumed. As already mentioned, as a matter of fact, a part of methane is burnt to produce the heat necessary to reactions. The methane combustion reaction is  $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$ , from which it is possible to infer that in the combustion there is an emission of 2.75 g of  $\text{CO}_2$  every g of  $\text{CH}_4$  burnt. Therefore, every gram of methane consumed in the reforming process (burnt for heat production or reformed to produce hydrogen) there is the emission of 2.75 g of  $\text{CO}_2$ .

The actual consumption can be expressed according to the process efficiency. Indicating with  $m_{\text{H}_2}$  the mass of hydrogen produced and with  $\text{LHV}_{\text{H}_2}$  its lower heating value, with  $m_{\text{CH}_4}$  the mass of methane consumed and with  $\text{LHV}_{\text{CH}_4}$  its lower heating value, by definition, the efficiency of the reforming process  $\eta_R$  is:

$$\eta_R = \frac{m_{\text{H}_2} \cdot \text{LHV}_{\text{H}_2}}{m_{\text{CH}_4} \cdot \text{LHV}_{\text{CH}_4}} \quad (4.128)$$

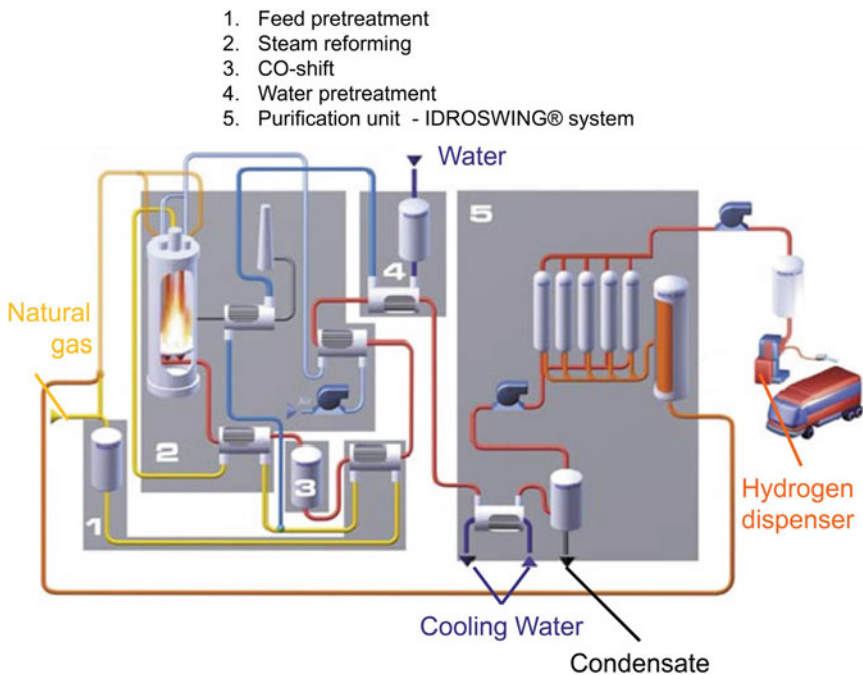
Thus the mass of methane consumed is:

$$m_{\text{CH}_4} = \frac{m_{\text{H}_2} \cdot \text{LHV}_{\text{H}_2}}{\eta_R \cdot \text{LHV}_{\text{CH}_4}} \quad (4.129)$$

Indicating with  $\text{EM}_{\text{sCO}_2}$  the  $\text{CO}_2$  emissions per g of  $\text{CH}_4$  consumed, the  $\text{CO}_2\text{EM}_{\text{CO}_2}$  emissions are:

<sup>36</sup> The necessary heat is produced by the combustion of a given quantity of methane.

<sup>37</sup> Also at high temperatures and pressures, the reaction is never complete.



**Fig. 4.68** Scheme of a reforming plant

$$EM_{CO_2} = m_{H_2} \frac{LHV_{H_2}}{\eta_R \cdot LHV_{CH_4}} \cdot EM_{sCO_2} \quad (4.130)$$

Assuming an efficiency of the reforming plant scheme accounting for 75%, from (4.130) it is possible to obtain:

$$EM_{CO_2} = m_{H_2} \cdot 9.13 \quad (4.131)$$

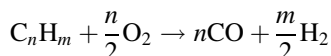
Therefore, there are emissions of 9.13 g of  $CO_2$  for every gram of hydrogen produced.

Figure 4.68 schematically shows a reforming plant. These are generally, large plants, with a production capacity around 800 MNm<sup>3</sup>/year of hydrogen.

#### 4.3.1.2 Partial Non-catalytic Oxidation of Hydrocarbons

Partial oxidation consists in the reaction of hydrocarbons with oxygen. The temperature at which the oxidation reaction occurs depends on the hydrocarbon and on the presence of catalysts: light hydrocarbons react, with the catalyst, at nearly 600°C, whereas heavy hydrocarbons (for instance *naphtha*), in the absence of catalysts, need temperatures around 1,400°C.

The overall efficiency of the partial oxidation process, on average amounting to 50%, is lower than the reforming one, and costs are remarkably higher. Furthermore, for the partial oxidation reaction, pure oxygen is needed: the exothermal reaction of partial oxidation of a general hydrocarbon  $C_nH_m$  is the following:



The product of partial oxidation of hydrocarbons is a synthesis gas made up of a mix of CO and  $H_2$  (similar to the one obtained in the first reaction of the reforming process) with a content in  $H_2$  that increases as the H/C ratio of the oxidised hydrocarbon increases.

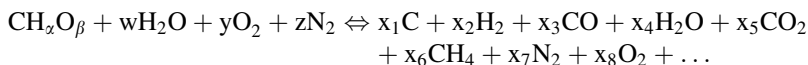
### 4.3.1.3 Gasification

In general, *gasification* consists in the oxidation of a (solid) substance whose final objective is the production of a gaseous fuel. The oxidising agent can be air, oxygen, water steam or a mix of them.

The gasification process takes place in *three subsequent phases*:

1. *Drying* at a temperature of nearly 100°C.
2. *Pyrolysis* at temperatures between 200 and 700°C.
3. *Oxidation–reduction processes* at temperatures around 900°C.

The reaction processes are in variable percentages, according to the starting substance, the oxidation agent and the gasification technology used, hydrogen, carbon monoxide, carbon dioxide, steam, methane and hydrocarbons exceeding the status of vapours or oils and ashes. The general gasification reaction of a  $CH_xO_\beta$  substance is the following:

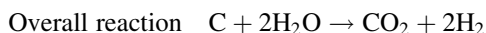
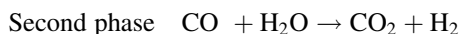
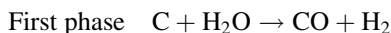


### Coal Gasification

In *coal gasification*, carbon reacts with water steam according to the reaction  $C + H_2O \rightarrow CO + H_2$ . This is an endothermic reaction and the relevant balance, at low temperatures, is heavily shifted to the left. Therefore, this reaction must be carried out at high temperatures (800–1,000°C), which are kept through the combustion of a part of coal with dosed inlets of air or oxygen or heat from a combustion chamber. The reaction described represents the first phase of the process. Subsequently, the mix  $CO + H_2$  produced (synthesis gas called *water gas*), also containing small percentages of  $CO_2$ , is subtracted from the equilibrium, enriched with a suitable quantity of water steam and passed through catalysts (with

iron and cobalt) at temperatures of nearly 400°C, similar to the case of the reforming process. In this way a reaction occurs, called *water gas conversion reaction*:  $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$ .

In brief this process, with a global efficiency of around 50%, is:



Proceeding similarly to the reforming process, it is possible to calculate CO<sub>2</sub> emissions for the production of hydrogen from coal gasification: assuming an efficiency of the gasification plant of 50% CO<sub>2</sub> emissions amounting to 30 g per g of hydrogen produced are obtained.

### Gasification of Biomass

One of the most advanced systems for the gasification of biomass is represented by two fluid beds in which combustion and gasification occur separately to produce a gas not diluted with nitrogen. In this case (*fluid bed indirect heating gasifier*) an oxygen generator is not necessary and there are no problems in the materials for heat transportation to high temperatures. This type of plant allows a high conversion of the carbon present in the biomass, which can be used also in a non-dried state.

The output synthesis gas from the gasifier must be treated before being used in combustion engines, turbine or high temperature fuel cells. There are two main gas conditioning methods that are substantially used: *cold* and *hot*.

The *cold methods* consist in the mechanical removal of particles through porous membranes (bag filters) or sand (sand filters) or water jets (scrubber); although sophisticated in their realisation, they are conceptually very simple and do not need in-depth analyses.

In *hot methods* the first cleaning stage is always represented by a cyclone, which removes the entire char<sup>38</sup> and part of the TAR (*Topping Atmospheric Residue*)<sup>39</sup> and of the particulate. The subsequent stages remove the fractions of TAR and particulate (ceramic filters) not removed by cyclones. Where possible these methods, are preferred, since they mostly retrieve the thermal and chemical content of the gas produced, do not have to cool the gas and do not produce polluted wastewater.

The *efficiency* of these plants, defined as the ratio between the energy content of the synthesis gas produced and the one of the biomass used, is on average 70%.

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<sup>38</sup> Carbonaceous solid product mainly made up of carbon, containing residues at a high molecular weight, as furan-derivatives and phenol compounds.

<sup>39</sup> "Liquid oily" fraction containing water and compounds with a low molecular weight as aldehydes, acids, ketones, alcohols, heavy hydrocarbons condensed at temperatures lower than 20–100°C.

#### 4.3.1.4 Pyrolysis (or Dry Distillation)

*Pyrolysis* is a process of thermochemical decomposition of organic matter based on the administration of heat at temperatures between 400 and 800°C, in a total absence of an oxidising agent, or with a reduced quantity of oxygen. In practice, thanks to this process, the organic macromolecules break into chains with a lower molecular weight. The products of pyrolysis are gaseous, liquid and solid, in proportions that depend on the methods of pyrolysis (fast, slow or conventional) and on the reaction parameters:

- from *conventional pyrolysis* that occurs at temperatures lower than 600°C and with moderate reaction times, it is possible to obtain approximately *three fractions (solid, liquid and gas)* in equal proportions;
- in *fast pyrolysis* the conversion reactions occur fast and at temperatures between 500 and 650°C, and with short contact times in order to reduce the new formation in intermediate compounds, hence favouring the production of the *liquid fraction* up to 70–80% in weight of the organic matter supplied;
- the *flash pyrolysis* takes place at temperatures exceeding 700°C and with contact times lower than 1s, in such a way as to favour the production of a *liquid fraction* (around 80% in weight of supply), but with a more reduced composition variation.

#### 4.3.1.5 Fermentation

*Fermentation* is an anaerobic process, similar to the known process of anaerobic digestion, in which the glucose of biomass is decomposed, through bacteria, into hydrogen, carbon dioxide and acids according to the following reaction:



The theoretical efficiency is 4 mole of hydrogen per mole of glucose (0.5 Nm<sup>3</sup> of hydrogen per hk equivalent glucose). The final co-products of fermentation as acetic acid can be further fermented or submitted to photosynthesis processes, increasing the maximum theoretical efficiency to 12 mole of hydrogen per mole of equivalent glucose. The bacteria necessary to fermentation can be cultured in pure or mixed cultures. Pure cultures of *caldicellulosirupter saccharolyticus* and *thermotoga elfii* can produce hydrogen at temperatures of 65°C. Mixed cultures of *clostridia* use non-sterile environments in continuous reactors at nearly 30°C on substrates of carbohydrates including cellulose.

The research is oriented towards obtaining mixed cultures in non-sterile environments with a high hydrogen efficiency and able to inhibit the consumption of the hydrogen produced.



### 4.3.1.6 Photoproduction

*Hydrogen photoproduction* can be obtained by using some photosynthetic organisms including green algae. It is performed by conditioning algae through illumination cycles alternated to darkening cycles. Algae cause bio-photolysis by splitting water into  $H_2$  and  $O_2$ . In some conditions, the *hydrogenase* enzyme contained in green algae acts as a catalyst causing the reduction of protons to form hydrogen. *Hydrogenase* is synthesised after many hours of incubation in anaerobic (without oxygen) conditions and without light. *Hydrogenase* contains iron and is oxygen-sensitive, so that when after a short period of light exposure in which  $H_2$  and  $O_2$  are produced, the production of hydrogen decreases. Green algae as *chlamydomonas reinhardtii*, blue algae as *cyanobacteria* and photosynthetic bacteria as *rhodobacter sphaeroides* have been extensively tested. Blue algae and bacteria produce hydrogen by using the *nitrogenase* enzyme, normally involved in the formation of  $NH_3$ . *Nitrogenase* is less efficient than *hydrogenase* (due to a higher energy demand and a slower turnover). The reactor must be designed to allow the collection of the hydrogen produced, be penetrable to light, water and culture.

## 4.3.2 Thermal Energy Transformation Plants

### 4.3.2.1 Absorption Heat Pumps

#### Operational Principle

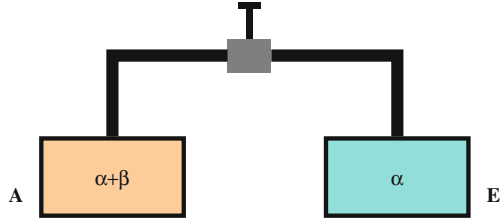
Absorption heat pumps operate on the basis of the capacity of some substances to absorb large quantities of steam of others, hence forming a mix or forming weak chemical bonds.

The principle at the basis of the operation of absorption machines is based on the behaviour of liquid mixtures in equilibrium with their own vapour.

To analyse the phenomena determining the operation of these machines, two containers shall be considered: A (absorber) and E (evaporator), the former (A) containing a mix of substances  $\alpha$  and  $\beta$  (i.e.: liquid in equilibrium with its vapour) and the latter (E) substance  $\alpha$  alone (also in this case in liquid phase in equilibrium with vapour). The two containers communicate through an initially closed tap, as shown in Fig. 4.69. In these conditions it is possible to express pressure in A ( $p_A$ ) and pressure in E ( $p_E$ ) according to the concentrations ( $X_\alpha$  and  $X_\beta$ ) and the partial pressures of the vapour phase ( $p_\alpha$  and  $p_\beta$ )<sup>40</sup> of the two solutions through the Raoult's Law. In container A there is a solution of  $\alpha$  and  $\beta$ , therefore:

<sup>40</sup> In the presence of the two phases of liquid and steam, the pressures of the steam phase ( $p_\alpha$  and  $p_\beta$ ) only depend on the temperatures existing in containers ( $T_A$  and  $T_E$ ).

**Fig. 4.69** Diagram of the operation of absorption heat pumps



$$P_A = X_\alpha P_\alpha + X_\beta P_\beta \quad (4.132)$$

In container  $E$  there is pure  $\alpha$ , therefore:

$$P_E = P_\alpha \quad (4.133)$$

If substance  $\alpha$  is more volatile than  $\beta$ , that is if  $P_\alpha \gg P_\beta$  (4.132) can be as follows:

$$P_A = X_\alpha P_\alpha \quad (4.134)$$

The Clapeyron's Law links temperature and pressures in a biphasic system through the following ratio:

$$\frac{dP}{dT} = \frac{\Delta H}{T \Delta V} \quad (4.135)$$

where  $\Delta V = V_v - V_l$  is the variation of volume in the passage of phase from vapour ( $V_v$ ) to liquid ( $V_l$ ) and  $\Delta H$  is the latent heat of evaporation.

Putting aside the volume of the liquid compared to the one of vapour ( $\Delta V \cong V_v$ ), considering vapour as a perfect gas and  $\Delta H$  constant, it follows that:

$$\frac{dP}{dT} = \frac{\Delta H}{RT^2} P \Rightarrow \frac{dP}{P} = \frac{\Delta H}{R} \frac{dT}{T^2} \quad (4.136)$$

Integrating (4.136) and indicating with  $K$  the constant of integration, it follows:

$$\ln P = -\frac{\Delta H}{R} \frac{1}{T} + K \quad (4.137)$$

Therefore the pressure of the steam phase of substance  $\alpha$  according to temperature is:

$$P_\alpha = e^{-\frac{\Delta H}{RT} + K} \quad (4.138)$$

From (4.133) it follows:

$$P_E = e^{-\frac{\Delta H_\alpha}{R T_E} + K_1} \quad (4.139)$$

From (4.134) it is obtained:

$$P_A = X_\alpha \cdot e^{-\frac{\Delta H_\alpha}{R T_A} + K_1} \quad (4.140)$$

By putting the two containers in communication, obviously the pressures in A and E will be the same; from (4.139) and (4.140) therefore it follows:

$$e^{-\frac{\Delta H_\alpha}{R} \frac{1}{T_E}} = X_\alpha \cdot e^{-\frac{\Delta H_\alpha}{R} \frac{1}{T_A}} \quad (4.141)$$

Moving on to logarithms:

$$-\frac{\Delta H_\alpha}{R} \frac{1}{T_E} = \ln X_\alpha - \frac{\Delta H_\alpha}{R} \frac{1}{T_A} \quad (4.142)$$

From (4.142) it is obtained:

$$\frac{1}{T_A} = \frac{R}{\Delta H_\alpha} \ln X_\alpha + \frac{1}{T_E} \quad (4.143)$$

Being  $\Delta H_\alpha > 0$  and  $0 < X_\alpha < 1$ , therefore  $\ln X_\alpha < 0$ , it is possible to obtain:

$$\frac{1}{T_A} > \frac{1}{T_E} \Rightarrow T_A < T_E \quad (4.144)$$

The variation of concentration (in E there is a pure  $\alpha$  whereas in A there is a solution of  $\alpha$  and  $\beta$ ) at the same pressure conditions, therefore the temperature in A is lower than temperature in E. From (4.144) it is evident that (R being a constant) the difference between temperature in A and in E increases as both  $X_\alpha$  (that is to say the concentration of  $\alpha$  must be low) and  $\Delta H_\alpha$  decrease (which means that the latent heat of evaporation of  $\alpha$  must be as low as possible<sup>41</sup>).

#### *Description of the Absorption Heat Pump Plant*

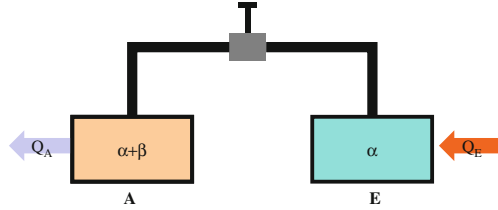
As regards Fig. 4.70, providing heat ( $Q_E$ ) in E there is the production of steam of  $\alpha$ , which migrates to A. By subtracting heat ( $Q_A$ ) from A the steam previously formed goes back to the liquid state and, thanks to the affinity between  $\alpha$  and  $\beta$  is absorbed by the solution contained in A. This system can be therefore used for the operation of a heat pump taking heat ( $Q_E$ ) to a certain temperature and releases it ( $Q_A$ ) at a lower temperature (4.144). However, in the process described, the variation of concentrations in E, as well as the exhaustion of  $\alpha$  in E, allow that, at a certain point, the process itself stops. In order to make this system cyclical, it is necessary to bring the two containers back to their initial conditions. To this purpose, other two exchangers are used (Fig. 4.71): a steam generator (G), that absorbs heat  $Q_G$  at temperature  $T_G$  and a condenser that releases heat  $Q_C$  at temperature  $T_C$ .

Summing up, as regards Fig. 4.71, the components of an absorption heat pump are the following:

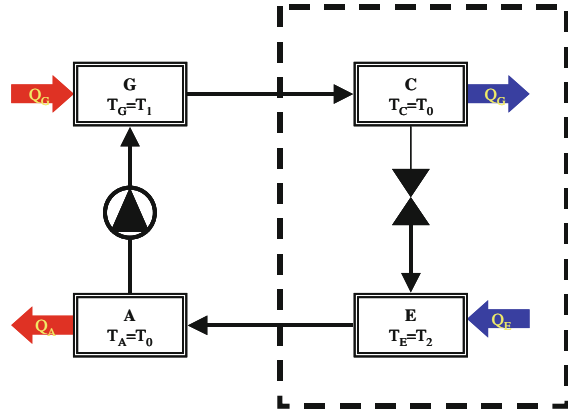
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<sup>41</sup> That is in line with the hypothesis according to which  $\alpha$  is far more volatile than  $\beta$ .

**Fig. 4.70** Operational diagram of the absorber–evaporator system



**Fig. 4.71** Operation scheme of an absorption heat pump



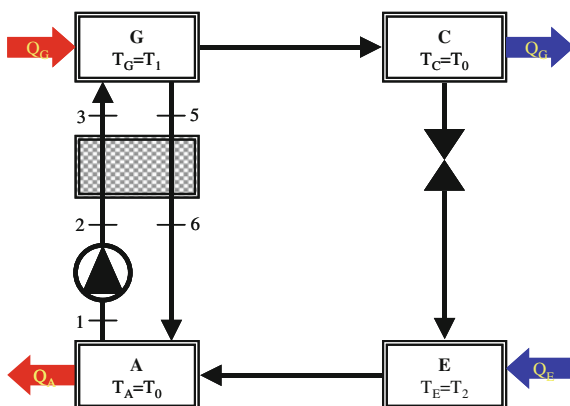
- *Steam generator (G)*: here the fluid absorbs heat  $Q_G$  at temperature  $T_G$ . This entails an evaporation of the mix with its subsequent dilution<sup>42</sup>;
- *Condenser (C)*: here the fluid releases heat  $Q_C$  at temperature  $T_C$  by condensing it at high pressure;
- *Evaporator (E)*: between it and the condenser there is a pressure difference (through a valve) ( $p_E < p_C$ ) that allows the refrigerant to evaporate by absorbing heat  $Q_E$  at temperature  $T_E$ ;
- *Absorber (A)*: here the refrigerant is reabsorbed by the solution, completing the cycle. The absorption causes the condensation of the refrigerant, therefore it is necessary to subtract heat  $Q_A$  (at temperature  $T_A$ ).

As mentioned above, the cycle of an absorption heat pump is based on the use of a binary mix of fluids, for instance a solution of water and lithium bromide ( $\text{H}_2\text{O}-\text{BrLi}$ ), or ammonia and water ( $\text{NH}_3-\text{H}_2\text{O}$ ). The first of the two substances of the mix behaves as a *refrigerant fluid*; the second as *solvent*, in which the refrigerant is dissolved in a more or less high concentration according to the point of the plant.

To keep the necessary difference of pressure between condenser and evaporator<sup>43</sup> (and, therefore, between steam absorber and generator) it is necessary to

<sup>42</sup> Being  $\alpha$  more volatile than  $\beta$ , the steam will be richer than  $\alpha$  compared to the liquid phase.

<sup>43</sup> Normally the pressure at the condenser is nearly 10 times as much as higher than the one at the evaporator.

**Fig. 4.72** Scheme of a plant with an absorption heat pump

insert a laminating valve between condenser and evaporator and a pump between steam absorber and generator.<sup>44</sup>

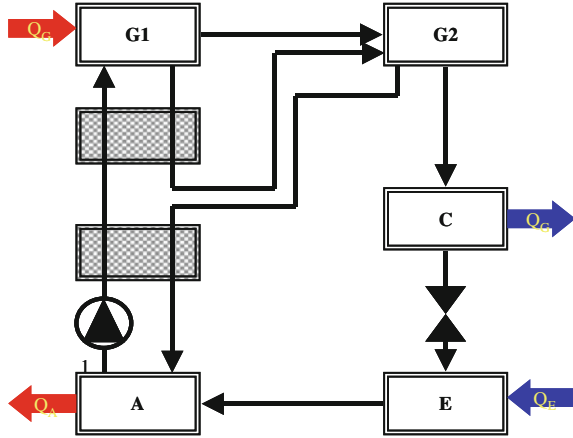
Figure 4.72 shows a more detailed diagram of the operation cycle of an absorption heat pump. The cycle uses a solution of water and lithium bromide, which is represented here as an example with the values indicating the typical values of the cycle (concentrations, temperatures and pressures).

At the exit of the absorber (section 1) the solution is rich in refrigerant ( $X_\alpha = 59\%$ ,  $X_\beta = 51\%$ ) and is at a pressure of 800 Pa and at a temperature of 41.5°C. Unless load losses occur, the pressure in the evaporator is the same available in the absorber, a pressure at which water evaporates at around  $5 \div 6^\circ\text{C}$ .

The solution (at the liquid state) taken by the absorber is compressed at a constant temperature through the pump and in section 2 the pressure is nearly 8,000 Pa: from here the solution enters the heat exchanger (where it exchanges heat with the solution outgoing from the steam generator) heating up to a temperature of nearly 77°C, at a constant pressure and concentration. In the steam generator (where heat  $Q_G$  is absorbed) there are two phases: in the first one there is a heating (up to nearly 85°C) at constant pressure and concentration; in the second one, being the solution in equilibrium with its steam, at an increase of temperature corresponds a separation (through evaporation) of the refrigerant from the solution. Pressure remains constant also in this second phase, at the end of which there is a pure refrigerant at the vapour state and a solution at the liquid state rich in solvent ( $X_\alpha = 36\%$ ,  $X_\beta = 64\%$ ) at the temperature of nearly 94°C. The liquid solution is introduced in the exchanger where it heats the solution coming from the absorber; from here it is sent to the absorber itself, providing it with a solution, rich in solvent, able to absorb the refrigerant. The refrigerant is sent to the condenser, where it condenses by releasing heat  $Q_C$  at a high temperature (94°C). From here it

<sup>44</sup> Also in this type of pumps, therefore, there is a compression: however, compared to the case of compression heat pumps where a gas is compressed through a compressor, in the absorption ones a liquid is compressed through a pump, and therefore the compression work is much smaller.

**Fig. 4.73** cycle of a plant with a two-stage absorption heat pump



crosses the laminating valve, decreasing its pressure (from 8,000 to 800 Pa) and it is injected in the evaporator, where it evaporates by absorbing heat  $Q_E$  at the temperature of nearly 5°C. At this point the refrigerant (at the vapour state) is taken from the evaporator and introduced in the absorber by closing the cycle.

The absorption plant can take a more complex configuration: in fact in order to improve the efficiency of the cycle two-stage concentrators are used (Fig. 4.73). In this case the steam generator is divided into two sections, one at *high* and one at *low* temperature.

#### *Performance of Absorption Heat Pumps*

The performance of an absorption heat pump are generally indicated with a defined Coefficient Of Performance (COP) code; in this case, as a ratio between the useful (thermal power) heat flow ( $Q_u$ ) and the thermal power introduced in the steam generator  $Q_G$

$$\text{COP} = \frac{Q_u}{Q_G} \quad (4.145)$$

As regards Fig. 4.72, in the heating operation there is:

$$\text{COP} = \frac{Q_A}{Q_G} \quad (4.146)$$

Whereas in the cooling phase:

$$\text{COP} = \frac{Q_E}{Q_G} \quad (4.147)$$

The COP values in the heating operation are around 1.5, whereas in the cooling phase they are markedly lower. For simple machines, they are typically lower: the

value of COP varies in the range 0.6–0.75, with higher values for lithium bromide machines compared to the ammonia ones: In the case of double effect machines, the COP can reach values exceeding the unit, generally in the range of 1.1–1.3. Furthermore, performance vary if the machine works in a partial load. In this connection, it is possible to observe that an absorption machine shows a lower consumption compared to a compression machine and in particular a partial load cooling COP can outperform the corresponding full load value. This is due to the absence, in absorption machines, of auxiliaries with parts in motion, whose performance always decrease with partial loads, and with the increase in the exchange efficiency in system exchangers when the system operates with ranges lower than the design ones.

## References

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